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A STUDY OF ELECTRONICS RADIATION HARDNESS ASSURANCE TECHNIQUES. VOLUME II, PART 2, ELECTRICAL SCREENING FOR IONIZING RADIATION RATE AND TOTAL DOSE EFFECTS

I. Arimura, et al

Boeing Company

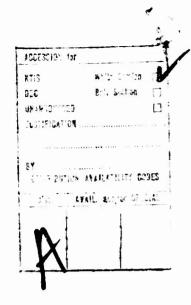
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This program determined physical failure modes of a range of discrete and integrated semiconductor devices exposed to ionizing rate, neutron, and total dose envirements. From physical reasoning possible electrical parameter measurements were determined which had some probability of correlating with the radiation sensitivity and failure thresholds. It was determined that base transit time normalization for neutron degradation was generally effective for low-power transistors, but ineffective for power devices. Other AC and a few DC measurements also were found to be effective potential screens for neutron degradation. No particular advantage was noted for using electrical storage time constant 3 compared to electrical storage time for screening primary photocurrents of low-power discrete devices. In some cases, the integrated circuits were obtained with nonstandard metallization, "special lead," topologies to enable electrical measurements to be made at internal circuit nodes. In this Volume (Volume II), the utility of these measurements as correlation parameters was compared to that obtained from measurements made using unmodafred circuits. Excellent correlation was obtained between the neutron degradation of the logic circuits and the emitter-base turn-on voltage obtained from the measurements made using special leads. Electrical screens for total dose hardness assurance were found to be relatively ineffective even with parameter correlation factors of 0.7 to 0.8. Similar results were obtained from an evaluation of the low dose screening concept since relative device sensitivity varied with absorbed dose. A mathematical expression was developed for the neutron induced reduction of the energy required for second

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A STUDY OF ELECTRONICS RADIATION HARNESSS ASSURANCE TECHNIQUES

Volume II, Part 2
Electrical Screening for Ionizing Radiation Rate and
Total Dose Effects

I. Arimura, et al.

The Boeing Company Seattle, Washington 98124

Final Report for Period 31 July 1970 through 16 July 1973

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FOREWORD

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Inclusive dates of research were 31 July 1970 through 16 July 1973. The report was submitted 29 October 1973 by the Air Force Weapons Laboratory Project Officer, Mr. John L. Mullis (ELP).

Principal authors and contributors were Mr. Allan H. Johnston, Dr. L. L. Sivo, and Mr. D. W. Egelkrout. Technical direction and coordination of the program were performed by Dr. R. S. Caldwell and Mr. C. Rosenberg.

Capt J. L. Guidry, Capt G. B. Crocker and Capt P. J. Vail at the Air Force Weapons Laboratory also made significant contributions to the overall planning and execution of the program.

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This technical report has been reviewed and is approved.

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PREFACE

This report describes the results of a comprehensive study which was designed to determine improved techniques for providing radiation hardness assurance on modern electronic systems. The two basic goals considered were (1) to determine from physical reasoning and large scale testing the effectiveness of established electrical screening parameters and the existence of additional ones which might be correlated with radiation responses and (2) to establish a statistical comparison between the various hardness assurance techniques including electrical screening, lot sampling and irradiate-and-anneal. For reasons of physical convenience, the report is divided into three volumes:

Volume I - Background, Approach, and Summary of Results

Volume II - Electrical Screening, parts 1, 2, and 3

Volume III - Lot Sampling and Irradiate-and-Anneal

This Volume (Volume II) contains a detailed description of the results obtained from the electrical screening portion of the program. The electrical screening approach examined correlations between certain initial electrical parameters and the radiation sensitivities of the devices. The correlation parameters were selected on the basis of physical reasoning and the radiation sensitivies were defined differently for the various radiation environments. Neutron hardness assurance is treated first and the various classes of devices such as low-power transistors, high-power transistors, JFETs and ICs are discussed separately. Ionizing radiation rate hardness assurance is treated second with subdivision determined again by the various classes of devices. MTBF results are also discussed for parts subjected to ionizing rate tests. Total dose hardness assurance is discussed third for the low-power transistors and for the op amp separately. Low dose screening is included in this section although it differs slightly from the "normal" techniques of electrical screening. Finally, second breakdown hardness assurance is discussed in its entirety.

CONTENTS

Section		Page
III	IUNIZING RADIATION RATE HARDNESS ASSURANCE	1
	1. INTRODUCTION	1
	2. LOW-POWER TRANSISTORS	1
	3. POWER TRANSISTORS	5
	4. JUNCTION FIELD EFFECT TRANSISTOR	6
	5. INTEGRATED C!RCUITS	8
	6. MTBF RESULTS FOR PARTS SUBJECTED TO IONIZING RATE TESTS	21
IV	IONIZING RADIATION TOTAL DOSE HARDNESS ASSURANCE	76
	1. INTRODUCTION	76
	2. ELECTRICAL SCREENING - LOW-POWER TRANSISTORS	76
	3. LOW DOSE SCREENING - LOW-POWER TRANSISTORS	81
	4. ELECTRICAL SCREENING - μΑ744 OPERATIONAL AMPLIFIER	83
	5. LOW DOSE SCREENING - μΑ744 OPERATIONAL AMPLIFIER	84
	References	117

1 LLUSTRATIONS

Figure		Page
49	Histogram of Primary Photocurrents at $5.3 \times 10^8 \text{ rad}(\text{Si})/\text{s}$ for $2\text{N}696$	23
50	Histogram of Primary Photocurrents at 1.35 x 10^{10} rad(Si)/s for 2N2222	24
51	Histogram of Primary Photocurrents at 6.0 x 10^9rad(Si)/s for 2N2905A	25
52	Histogram of Primary Photocurrents at $6.0 \times 10^{10} \text{rad(Si)/s}$ for 2N3960	26
53	Histogram of Primary Photocurrents at $\epsilon.0~\mathrm{x}$ $10^{10}~\mathrm{rad(Si)/s}$ for $2\mathrm{N}709$	27
54	Dose Rate Dependence of Mean Primary Photocurrent for 2N696 and 2N2905A	28
55	Dose Rate Dependence of Mean Primary Photocurrent for 2N2222 and 2N3960	29
56	Scatter Diagram of I_{pp} [5.3 x 10^8 rad(Si)/s] versus t_{SE} (50 mA/10mA) for 2N696	30
57	Scatter Diagram of I_{pp} [5.3 x 10^8 rad(Si)/s] versus τ_S for 2N696	31
58	Histogram of I_{pp} at 3.0 x 10^7 rad(Si)/s for TA8007 Showing Devices with "Anomalous" Photocurrents	32
59	Scatter Diagram of Base Doping Concentration. N_{BO} , versus Primary Photocurrent, I_{pp} , at 3.0×10^7 Rad(Si)/s) for TA8007	33
60	Scatter Diagram of r_B versus I_{pp} at 3.0 \times 10 7 rad(Si)/s for TA8007	34
61	Histogram of Threshold Rate for Turn-On $(I_{sp} = 2A)$ for RCA TA8007 in Shorted-base Configuration	35
62	Histogram of Threshold Rate for Turn-On (I_{sp} = 1A) for Solitron BR200A in Shorted-base Configuration	36
63	Scatter Diagram of $h_{\mbox{FE}}$ (3V/1A) versus Turn-On Threshold Rate for RCA TA8007	37

ILLUSTRATIONS (Cont'd)

Figure		Page
64	Scatter Diagram of $r_{\rm B}$ versus Turn-On Threshold Rate for RCA TA8007	38
65	Scatter Diagram of $h_{\mbox{\scriptsize FE}}$ (3V/1A) versus Turn-On Threshold Rate for Solitron BR200A	39
66	Scatter Diagram of r _B versus Turn-On Threshold Rate for Solitron BR200A	40
67	Superlinearity of Primary Photocurrent, I_{pp} as a Function of Dose Rate for the Dual JFET	41
68	Correlation Between $C_{\mbox{GSS}}$ (V=1V) and $I_{\mbox{pp}}$ for the Dual JFET	42
69	Correlation Between τ_{S} and \boldsymbol{I}_{pp} for the Dual JFET	43
7ù	A Sample Histogram of the Radiation Response Threshold Data [TI Inverter 1-State Response]	44
71	Histogram of TI Inverter 1-State Response Thresholds Showing Truncation With Electrical Storage Time	45
72	Truncation of TI Buffer Radiation Responses with Offset Voltage	46
73	Histogram of Radiation Response Threshold Data (Motorola Puffer 1-State Response)	47
74	Method Used to Detect Open Internal Resistors in the Inverter Circuits	48
75	Truncation of the Word Switch Secondary Photocurrent Thresholds with \mathbf{h}_{FE} and \mathbf{r}_{B}	49
76	Experimental Method Used in LINAC Tests of the Motorola Sense Amplifier	50
77	Illustration of the Relative Radiation Sensitivities of 2N709, 2N930 and 2N2905A	85
78	Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10^6 rads; I_E = 3 μA)	86
79	Histograms of I_B/I_B^0 Illustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose= 1.25 x 10^6 rads; $I_p = 3 \mu A$)	87

ILLUSTRATIONS (Cont'd)

Figure		Page
80	Histogram of h_{FE}/h_{FEO} lllustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10^6 rads; I_E = $100~\mu$ A)	88
81	Histogram of $\Delta(1/h_{FE}) = \Delta I_B/I_C$ Illustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10^6 rads; $I_E = 100~\mu\text{A}$)	, 89
82	Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose = 3.0 x 10^5 rads; $I_E = 1~\mu A$)	90
83	Histogram of I_B/I_B^0 Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose= 3.0 x 10^5 rads; I_E = 1 μ A)	91
84	Histogram of h_{FE}/h_{FEO} Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose = 3.0 x 10^5 rads; $I_E = 1$ mA)	92
85	Histogram of $\Delta(1/h_{FE})$ = $\Delta I_B/I_C$ Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose = 3.0 x 10^5 rads; I_E = 1mA)	93
86	Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6 x 10 rads; I_E = 3 μ A)	94
87	Histogram of I_B/I_B^0 Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6×10^6 rads; $I_E = 3 \mu A$)	95
88	Histogram of h_{FE}/h_{FEO} Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6×10^6 rads; $I_E = 3$ mA)	96
89	Histogram of $\Delta(1/h_{FE}) = \Delta I_B/I_C$ Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6 > 10^6 rads; $I_E = 3$ mA)	97

ILLUSTRATIONS (Cont'd)

Figure		Page
90	Histogram of Initial Gain, h_{FE} , Marked to Illustrate the Extent of the h_{FEO} Versus h_{FE} Correlation (Marked Devices Came From the Lower Tail of the h_{FE} (Dose) Histogram). [2N2905A, h_{FE} (10mA) \leq 64 at 1.3 x 106 rad] The Pronounced Structure in the Histogram is Due to the Different Wafers	98
91	Histogram of Initial Gain, h_{FEO} , Marked to Illustrate the Extent of the h_{FEO} Versus h_{FE} Correlation [Marked Devices Came From the Lower Tail of the h_{FE} (Dose) Histogram]. [2N930, h_{FE} (1mA) \leq 64 at 3.0 x 10^5 rad]	99
92	Histogram of Initial Gain, h_{FEO} , Marked to Illustrate the Extent of the h_{FEO} Versus h_{FE} Correlation [Marked Devices Came From the Lower Tail of the h_{FE} (Dose) Histogram]. [2N709, h_{FE} (1mA) \leq 19 at 1.3 x 10 ⁶ rad]	100
93	Histogram of Low Dose ΔI_B , Marked to Illustrate the Limitations of the Low Dose Screening. Marked Devices Came From the Upper Tail of the High Dose ΔI_B Histogram (2N930, High Dose = 3 x 10^5 rads)	101
94	Histogram of Low Dose ΔI_B , Marked to Illustrate the Limitations of the Low Dose Screening. Marked Devices Came From the Upper Tail of the High Dose ΔI_B Histogram (2N2905A, High Dose = 5.6 x 10^6 rad)	102
95	Histogram of Low Dose ΔI_B Marked to Illustrate the Limitations of the Low Dose Screening. Marked Devices Came From the Upper Tail of the High Dose ΔI_B Histogram (2N709, High Dose = 1.3 x 10^6 rad)	103
96	Histogram of the Initial Bias Currents Illustrating the Variation Among the Op Amps	104
97	Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the Op Ams (Dose = 5.6 x 10^6 rads)	105
98	Histogram of I_B (5.6 x 10^6 rad) Illustrating the Variation Among the Op Amps	106

TABLES

<u>Table</u>		Page
51	Summary of Low Power Transistors Tested for Transient Ionization Effects	51
52	Summary of Photocurrent Data for Low-Power Transistors	52
53	Comparison of Electrical Storage Time and Storage Time Constant, as Screening Parameters for Primary Photocurrent	53
54	Summary of Rank Correlation Coefficients for Various Screening Parameters versus I for Low-Power Transistors	54
55	Relative Efficacies of Various Screening Parameters for Primary Photocurrents	54
56	Summary of MLR Predictions of I_{pp} for 2N29C5A and 2N2222 Low-Power Transistors Using Total Sample	55
57	Summary of Rank Correlation Coefficients for sp	56
58	Summary of Rank Correlation Coefficients for Primary Photocurrent - Dual JFET	57
59	Summary of MLR for I - Dual JFET	58
6 0	Summary of TTL Transient Ionization Data	59
61	Some Rank Correlations for the $\overset{\bullet}{\gamma}$ Response of the TI Inverter	60
62	Some Rank Correlations for the $\overset{\raisebox{.5ex}{.}}{\gamma}$ Response of the TI Buffer	61
63	Some Rank Correlations for the Ionization Response Threshold of the TI A-0-I Gate	62
64	MLR Results for TI A-O-I Gate Transient Response Threshold	63
6 5	Some Rank Correlations for Ionizing Rate Response of the Motorola Inverter	64
66	Effects of Electrical Screens on the Regression Results for the Motorola Inverter 1-State γ	6 5

TABLE (Cont'd)

Table		Page
67	Some Rank Correlations for the $\overset{\bullet}{\gamma}$ Threshold of the Motorola Buffer	66
68	Regression Results for the Motorola Buffer $\boldsymbol{\gamma}$ Threshold	67
69	Summary of Ionizing Rate Data (Non-TTL Integrated Circuits)	68
70	Some Rank Correlation Factors for the Ionization Response of the Word Switch	69
71	Multiple Linear Regression Results for the I Threshold of the TI Word Switch sp	70
72	Some Rank Correlation Coefficients for the Ionizing Rate Response of the Motorola Sense Amp	71
73	An Example of MLR Predictions for the Ionizing Rate Response of the Motorola Sense Amp	72
74	Some Rank Correlation Coefficients for the Ionization Response of the μA744 Op Amp	73
75	MLR Results for the Ionization Response of the μA744 Op Amp	74
76	Failure Rates for Parts Subject to Ionizing Rate Tests	75
77	Rank Correlation Coefficients for Total Dose Damage Prediction (overview)	107
78	Summary of Data to Illustrate the Radiation Sensitivity of 2N709	108
79	Summary of Data +: Illustrate the Radiation Sensitivity of 2N930	109
80	Summary of Data to Illustrate the Radiation Sensitivity of 2N2905A	110
81.	Results of Rank Correlations Between Radiation Sensitivity (Low Dose) and Radiation Sensitivity (High Dose)	111
82	Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening (2N930)	112

TABLES (Cont'd)

Table		Page
83	Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening (2N2905A)	113
84	Summary of Data Illustrating the Procedure and the Results' of the Low Dose Screening (2N709)	114
85	Rank Correlation Coefficients for Damage Prediction at 5.6 x 10^6 rads - $\mu A744$	115
86	Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening for the $\mu A744$ Op Amp	116

ABBREVIATIONS AND SYMBOLS

Ampere, area, surface area of second breakdown region A Base area Emitter area Effective emitter area A_{EFF} A_{OL} Open-loop gain Cross Sectional area of a second breakdown site ASB AC Alternating current AH1 Effective emitter area determined from gain-bandwidth product, emitter base capacitance and current gain AH3 Effective emitter area determined from gain-bandwidth product, current gain, and base doping concentration AH4 Effective emitter area determined from gain-bandwidth product, breakdown voltage, and current gain A-0-I And-or-invert BOT Breakout transistor BVBreakdown voltage Breakdown voltage of collector-base junction with emitter open The emitter-base breakdown voltage of a transistor BVERO with the collector open $^{\rm BV}{\rm GSS}$ Breakdown voltage of gate-channel in JFET. Source and drain shorted **BVCBO** Base to collector breakdown voltage, emitter open **BVCEO** Open base collector to emitter breakdown voltage, measured at a collector current of 10 milliamperes **BVEBO** Open collector, emitter to base breakdown voltage, measured at a base current of 10 milliamperes C Damage factor, average specific heat, capacitor

 C_{CB} Collector-base junction capacitance

Gate-channel junction capacitance of JFET c_{GSS}

 C_{IB} Emitter-base junction capacitance

Collector-base junction capacitance COR

Damage factor of wafer transistors $C_{\mathbf{p}}$

 C_{SBL} Linear second breakdown neutron degradation constant

CB Neutron damage factor

C-B Collector to base

CB - X, Y Neutron damage factor for current gain measured at a collector current of X amperes and collector to emitter voltage of Y volts

C-E Collector to emitter

CH Channel

CMRR Common-mode rejection ratio

Coefficient of variation COV

Covariance = standard deviation COVAR

Cathode ray oscilloscope CRO

Linear second breakdown neutron degradation constant **CSBLXYZ**

determined from neutron levels ϕ_x , ϕ_y , and ϕ_z

 C_{SB} determined from neutron levels ϕ_x , ϕ_y , and ϕ_z **CSBXYZ**

Diffusion constant D

Diffusion constant for minority carriers in base region $D_{\mathbf{R}}$

Diffusion constant for minority carriers in emitter D_{E}

region

DC Direct current

D.I. Dielectric isolation

DUT	Device under test
Е	Energy or electric field strength, second breakdown energy measured at I _E = 5A
E-5MSIA	Second breakdown energy for a 5 millisecond wide, 1 ampere pulse of emitter current
E-5MSIBO	Second breakdown energy for a 5 millisecond wide voltage pulse equal to the collector-emitter breakdown voltage, base open
ESB	Energy required to produce second breakdown: measured at device terminals
E _{SB}	Energy required to produce second breakdown: delivered to a localized site of second breakdown
F	F value
FSC	Fairchild Semiconductor Corporation
FM1	Transistor figure of merit determined from gain bandwidth product and base doping concentration
FM3	Transistor figure of merit determined from gain bandwidth product and collector to base breakdown voltage, emitter open
FM4	Transistor figure of merit determined from gain bandwidth product and collector to base breakdown voltage, emitter open
FT	A constant proportional to the gain-bandwidth product measured at an emitter current of 1 ampere
на	Hardness assurance
HFE - X, Y	Common emitter DC current gain measured at a collector current of X amperes and a collector to emitte, voltage of Y volts
I	Current
I _B	Base current (bipolar transistors) or input bias current (op amps, sense amps)
I_B^o	Initial (pre-radiation) base current or bias current
I_B^s	The surface component of the base current

I _{B1}	The forward current into the base of a saturated transistor
I _{B2}	The current flowing out of the base of a saturated transistor when it is switched out of saturation
I _{BIAS}	Input bias current
IBS	Base current of saturated transistor
^I c	Collector current
СВО	Collector-base junction leakage current
^I cc	Power supply current in positive supply lead
I _{CC(0)}	Power supply current of a digital circuit in a 0-state
I _{CO}	Pre-exponential saturation current
^I cs	Collector current of saturated transistor
IDS	Drain current in JFET
IDSS	Source to drain saturation current at zero gate bias
I _E	Emitter current
IERO	Emitter-base junction leakage current, collector open
I _{EBO}	Initial (pre-radiation) emitter-base junction leakage current, collector open
I _{EBO}	The surface component of the leakage current across the reverse biased emitter-base junction
IEE	Power supply current in negative supply lead
IF	Forward current of gate-channel diode in JFET
I _{IN(R)}	Reverse input current measurement for TTL circuits
I _{IN(0)}	Current out of TTL input with input voltage low
I _{IN(1)}	Current into TTL input with input voltage high
I _{OS}	Input offset current
Ipp	Primary photocurrent

I _{OL}	Output leakage current of an integrated circuit
$\mathbf{I}_{\mathbf{R}}$	Reverse current of gate-channel diode in JFET
ISK	The output sink current of a TTL device with lower than normal supply voltage
Isp	Secondary photocurrent
IC	Integrated Circuit
ICBO	Open emitter, collector to base leakage current measured at 50 volts
ICEO	Open base, collector to emitter leakage current measured at 30 volts
IEBO	Open collector, emitter to base leakage current at 5 volts
I'V'	Portion of second breakdown power not directly dissipated in a second breakdown site
J _E	Emitter current density
J.I.	Junction isolation
k	Damage constant, an abbreviation for Kilo-ohm used in circuit schematics
Ka	Thermal conductivity at second breakdown site averaged over temperature
$\kappa_{ m F}$	Carrier removal damage factor
$K_{\widetilde{N}}$	Total delay time normalized damage constant
K _R	Damage constant due to lifetime degradation in emitter- base depletion region
L	Diffusion length, length of JFET channel in direction paralleled to current flow
^L c	Diffusion length of minority carriers in collector region
L _E	Diffusion length of minority carriers in emitter region

LINAC	Linear accelerator
LSI	Large scale integration
М	Mass of material at a localized second breakdown site
M_{β}	Temperature sensitivity of the common emitter DC current gain
MB -3.0	Temperature sensitivity of the common emitter current gain measured at a collector current of 3 amperes and a collector to emitter voltage of 3 volts
MeV	Mega electron volts
MLR	Multiple linear regression
MLRP	Multiple linear regression prediction
MLR-R	Coefficient of multiple linear correlation
MLR-r	Multiple linear regression partial correlation coefficient
MLRr	Multiple linear regression coefficient
MOT	Motorola
MSI	Medium scale integration
MTBF	Mean time between failure
N	Value of exponent in the equation relating second breakdown energy and neutron fluence. N is determined from, carrier concentration 4 fluence levels
N _B	Base doping concentration
N BO	Base doping concentration adjacent to emitter region
NE	Minority carrier density in the emitter region
No	Channel doping concentration for JFET in cm^{-3}
NXYZ	Value of exponent in equation relating second breakdown energy and neutron fluence. NXYZ is determined from fluence levels of ϕ_x , ϕ_y and ϕ_z
N(CH)	Channel doping as calculated from BV GSS measurements

Noise	$(1/f)_{s}$	Surface	component	of	the	1/f	noise	
-------	-------------	---------	-----------	----	-----	-----	-------	--

	s surrect component of the 1/1 holde
P	Power
P _{5B}	Power of a square pulse required to produce second breakdown
Q	A symbol for transistors used in schematic diagrams
R	Resistance
R _B	External resistance from the base of a transistor in an electrical circuit
$R_{\overline{D}}$	Maximum percentage range in the data
R_{E}	Radius of emitter region
R _L	Load resistor
^{R}P	Maximum percentage range in the prediction
RBC	The reciprocal of base impurity concentration
RBV	A constant inversely proportional to the 2.8 power of the open collector-emitter, to base breakdown voltage measured at a base current of 10 milliamperes
RCA	Radio Corporation of America
RCC	The reciprocal of the collector impurity concentration
RCV	A constant inversely proportional to the 2.8 power of the open emitter, collector to base breakdown voltage measured at a base current of 10 milliamperes
RMS	Root mean square
S	Switch
Sat.	Saturation
SB	Second breakdown
SCR	Silicon controlled rectifier
SLR	Single linear regression
SSI	Small-scale integration

T Absolute temperature (°K), Temperature

T Ambient temperature

Toff The turn-off time of an integrated circuit

t_{SB} The temperature at a site of second breakdown at the onset

of second breakdown

TI Texas Instruments

TTL Transistor-transistor logic

TUT Transistor under test

V Volt

 ${\bf V}_{{\bf BE}}$ Base to emitter voltage

 $\mathbf{v}_{\mathtt{BEON}} \qquad \qquad \mathtt{Emitter} \ \ \mathtt{to} \ \ \mathtt{base} \ \ \mathtt{forward} \ \ \mathtt{voltage}$

V_C Collector voltage

 ${
m V}_{
m CB}$ Collector to base voltage

V_{CC} The positive supply voltage of an integrated circuit

V_{CE} Collector to emitter voltage

 $v_{\text{CE(SAT)}}$ Collector to emitter voltage for saturated transistor

 ${\rm V_{DS}} \qquad \qquad {\rm Drain\ voltage}$

 $\mathbf{V}_{\mathbf{EB}}$ The voltage from the emitter to base of a transistor

 $\mathbf{v}_{\mathtt{EE}}$ The negative supply voltage of an integrated circuit

V_{GS} Gate to source voltage

 $V_{\mbox{\scriptsize fn}}$ Input voltage

 $V_{\mbox{IN(R)}}$ The reverse input voltage of a TTL circuit

 v_{OH} The 1-state output voltage of a digital circuit

 \mathbf{v}_{OL} The 0-state output voltage of a digital circuit

v _{os}	The offset voltage of an integrated circuit
$v_{\mathbf{p}}$	Pinch off voltage for JFET
V _{SB}	Voltage across a device prior to second breakdown
V-I	Voltage-current
VBEON-X	Emitter to base forward voltage for an emitter current of \boldsymbol{X} amperes
VCES-X	Collector to emitter saturation voltage at a collector current of \boldsymbol{X} amperes
VSB-5A	Voltage across a device prior to second breakdown at an emitter current of 5 amperes
VSB-5MSIBO	Voltage across a device prior to second breakdown at a delay time of 5 milliseconds and with zero base current
W_{B}	Base width
w _C	Collector depletion width of a transistor
W_{D}	Depletion region width of emitter-base junction
W _{1(2,3,4)}	Wafer number 1 (2,3,4)
WB	The inverse square root of the common emitter gain- bandwidth product
Z	Channel width in direction perpendicular to thickness and length in JFET
a	Channel thickness in JFET
С	Capacitance
cm	Centimeter
f _T	Common-emitter gain-bandwidth product
F_{α}	Common base cutoff frequency
g _m	Post-irradiation transconductance
g _{mo}	Pre-irradiation transconductance

h _{FE}	Common-emitter DC gain
h _{FE} ,h _{FEI}	Common-emitter DC current gain for inverted transistor
h _{FEO}	Pre-irradiation gain
h _{FE} ¢	Gain after neutron irradiation
in	Equivalent input noise current
k	Boltzmann constant
keV	10 ³ electron-volts
mA	10 ⁻³ amperes
mV	10^{-3} volts
mW	10^{-3} watts
n	Value of exponent in equation relating second breakdown energy and neutron fluence
ⁿ I	Exponent of voltage dependence of emitter-base junction capacitance
n _i	Electron concentration in intrinsic silicon
n p	Minority carrier density in a p-type semiconductor
ns	10 ⁻⁹ seconds
Po	Equilibrium hole concentration
pF	10 ⁻¹² farads
q	Electron charge
r	rads
rank-r	Rank correlation coefficient
r_{B}	Transverse base resistance
r _{B1}	Transverse base resistanc for inverted transistor
r	Collector body resistance

r_{cs} Resistance of collector region of saturated transistor

rd(on)o Pre-irradiation value of rd(on)

r_{d(on)} The on resistance of a JFET

rad(Si) A deposited dose of 100 ergs per gram of silicon

s Second

t Time

 t_R Base transit time

t_d Total delay time

t_{PD} Propagation delay time of a logic circuit

t_{OFF} Turn-Off time of the word switch

t_{PLH2} The delay time of an integrated circuit when the output goes from low to high, measured at 50% of the

equilibrium value

t_{rrGS} Reverse recovery time of gate-channel diode in JFET

 \mathbf{t}_{SE} Electrical storage time

t_{o.r} Saturation time of the word switch

t-statistic Measure of significance for multiple linear regression analyses

w_r Width of emitter stripe

x_ Modulation length

 ΔI_{R}^{S} (burn-in)The change in I_{R}^{S} during burn-in

 $\Delta I_B^s(T)$ The change in I_B^s when measured at different temperatures

 ΔI_{EBO}^{S} (burn-in) The change in I_{EBC}^{S} during burn-in

 ΔI_{EBO}^{S} The change in I_{EBO}^{S} when measured at different temperatures

Δn Excess electron concentration

 $\boldsymbol{\phi}_{\text{BE}}$ Base-emitter junction contact potential

Ω	Ohm
β	Grounded emitter DC current gain (i.e. h _{FE})
$^{\mathfrak{G}}\mathbf{F}$	Forced beta of saturated transistor (= I _{CS} /I _{BS})
β _o	Initial (pre-radiation) grounded emitter DC current gain
Ý	Ionizing dose rate
ε	Permictivity of dielectric
ε _o	Permittivity of vacuum
в	The electronic charge divided by the product of Boltzmann's constant and the absolute temperature
θ _{HS}	Hot spot thermal resistance
κ	Dielectric constant
μ	Mobility
$^{\mu}$ B	Carrier mobility in base region
^μ c	Carrier mobility in collector region
$^{\mu}n$	Electron mobility
$^{\mu}{}_{\mathbf{p}}$	Hole mobility
μ A	Micro amperes
μF	10 ⁻⁶ farad
μs	10 ⁻⁶ second
ρ _B	Resistivity of base region
^P C	Resistivity of collector region
ρSE	Emitter sheet resistivity
σ	Electrical conductivity or standard deviation
τ	Excess minority carrier lifetime
$\tau_{\mathtt{B}}$	Minority carrier lifetime in base region

$^{\tau}$ C	Minority carrier lifetime in collector region
τno	Minority carrier lifetime in highly p-type
τ _{po}	Minority carrier lifetime in highly n-type
τ s	Electrical storage time constant
τ_s	Storage time constant for gate-channel diode in JFET
$^{\tau}$ SB	Second breakdown delay time
^τ SBO	Delay time to second breakdown measured in previous tests
τ	Hot spot thermal time constant
ф	Neutron Fluence
$^{\phi}$ C	Critical dose or threshold dose for failure
ф ₁	First neutron fluence
ф ₂	Second neutron fluence
^ф 3	Third neutron fluence
Φ4	Fourth neutron fluence
$\omega_{\mathbf{T}}$	The gain-bandwidth product of a transistor (f $_{\rm T}$) x 2π
0-state	The low output voltage state of a digital circuit
1-state	The high output voltage state of a digital circuit
1N1	First neutron irradiation
2N1	Second neutron irradiation
3N1	Third neutron irradiation
4N1	Fourth neutron irradiation

SECTION III

IONIZING RADIATION RATE EFFECTS HARDNESS ASSURANCE

1. INTRODUCTION

This section discusses hardness assurance techniques for ionizing rate effects in discrete transistors, junction field-effect transistors (JFET), and integrated circuits. For discrete transistors, hardness assurance techniques were investigated for both primary and secondary photocurrent. The transistor types studied include high- and low-power transistors with a wide range of device geometries and electrical properties. The radiation rate dependence of primary photocurrent was also considered. For the JFET, gate primary photocurrent is the fundamental radiation parameter used in the correlation and hardness assurance studies. The integrated circuits included in this study are all dielectrically-isolated, radiation-hardened devices, and include both digital and linear circuit types. The circuit output response to ionizing radiation was used as the parameter of interest for hardness assurance and correlation studies. For the digital circuits, the radiation level was varied to find the particular radiation threshold level at which a given output response occurred.

A detailed description of the various device types and the schematic diagrams for the integrated circuits are contained in Paragraphs 2-a and 2-b, Section IV, Volume 1. A description of the radiation test conditions and techniques is included in Paragraph 4-c, Section IV, Volume 1.

2. LOW POWER TRANSISTORS

a. Primary Photocurrent

Steady-state primary photocurrents were measured for five types of low-power transistors and two types of IC breakout transistors using the Boeing Radiation Effects Laboratory 10-MeV Electron Linear Accelerator as an ionization source. Experimental details of the measurements were described previously in Paragraph 4-b, Section IV, Volume 1. Table 51 is a summary of the parts tested for primary and secondary photocurrents. The electrical screening parameters for primary photocurrents were investigated only for the first seven part types shown in Table 51.

The primary photocurrent, I $_{\rm pp}$, measured for five types of low-power transistors are summarized in the sample histograms shown on Figures 49 through 53. The mean, standard deviation, maximum, minimum and range of photocurrents are summarized in Table 52. The range of responses for these part types (given by the maximum I $_{\rm pp}$ divided by minimum I $_{\rm pp}$) varied from ~1.8 to ~3.5 (excluding one 2N3960 which exhibited a breakdown or anomalous I $_{\rm pp}$ a factor of 10 greater than the other devices of that type). However, the data at the very high rates are of questionabe accuracy, particularly for the rates in the high 10^{10} rad(Si)/s range. Accurate dosime by was difficult at these rates since the electron beam spot was quite small and the position of the beam varied from shot-to-shot.

 $_{
m pp}$, based on the simple theory given in Paragraph 3-a, Section V, Volume 1 for collector-base primary photocurrent, is expected to vary linearly with ionizing radiation rate. The rate dependence of $_{
m pp}$ is an important quantity to establish since extrapolation of data to other rates is generally required for analyses of system performance. The rate dependence of $_{
m pp}$ was established for four of the part types by measuring $_{
m pp}$ at two rates. Table 52 includes a summary of linearity of the rate dependence of $_{
m pp}$; the ratio of the photocurrent per unit rate at the higher and lower rates indicates the rate dependence is nearly linear for two of the part types with the 2N3960 and 2N2905A of questionable linearity. The linear dependence of $_{
m pp}$ with rate is shown in Figures 54 and 55 where the mean value of $_{
m pp}$ is plotted against dose rate for four of the part types. The bars associated with each data point are plus and minus one standard deviation for the distribution of photocurrents for the ~150 devices of each type.

The only well-known electrical technique for screening transistors against excessive photocurrents is the method of measuring electrical storage time, $t_{\rm SE}$, as developed by Carr (Ref. 17). The technique was originally developed to evaluate different device types and works fairly well for this purpose when restricted (1) to silicon planar diffused and mesa npn transistors with power ratings less than 800 mW, (2) to dose rates between 10^6 and 10^8 rad(Si)/s, and (3) to transistors with electrical storage times between 10^{-8} and 10^{-5} seconds. Although $t_{\rm SE}$ can be used

acceptably when comparing different types of devices, it has not been demonstrated to be useful as a screening parameter for devices of a given type.

However, as discussed in the theory of primary photocurrents (Paragraph 3-b, Section V, Volume 1), the main contribution to I pp originates almost entirely in the collector regions for non-Au-doped planar epitaxial devices. For these cases, the collector lifetime, $\tau_{\rm C}$, and diffusion length are the major parameters controlling I pp. The electrical screening and correlation parameter then is the electrical storage time constant, $\tau_{\rm S}$, rather than $t_{\rm SE}$ since,

$$\tau_{\rm S} \stackrel{\text{\tiny 2}}{=} 1/2 \ \tau_{\rm C}$$

where τ_{ς} is obtained from

$$t_{SE} = \tau_{S} \ln \frac{I_{B1} + I_{B2}}{I_{CS}/h_{FE} + I_{B2}}$$
 (12)

The results of the correlations between I and τ_S and τ_S are shown in Table 53. Electrical storage time constant, τ_S , appears to offer practically no improvement as a screening parameter over electrical storage time, t_{SE} . This is partly the result of the poor quality of the "fit" of the data to Equation (12) which produced "noisy" values of τ_S and thus poor rank correlations.

These results are further verified by examining the scatter diagrams (shown in Figures 56 and 57) of I $_{\rm pp}$ versus t $_{\rm SE}$ and $\tau_{\rm S}$ for one example in Table 53. It can be seen that, while a trend is obvious, these plots are truly scattered and neither of the parameters are particularly useful as a screen for I $_{\rm pp}$.

The efficacy of other screens for I $_{pp}$ were investigated. According to the theory presented in Paragraph 3-b, Section V, Volume 1, collector-base junction capacitance, $\rm C_{OB}$, and possibly base transit time, $\rm t_B$, should be the next best correlation parameters after $\rm \tau_S$. Neither of these parameters were particularly successful as I $_{pp}$ screens. The largest

correlation coefficient for C_{OB} was +0.538 for the 2N2905 which is opposite in sign to that anticipated. At least t_B , however poorly, correlated with the I_{pp} in the proper direction.

Tables 54 and 55 briefly summarize the order of efficacy of potential screening parameters for the various device types. In general, t_{SE} or τ_{S} are the best screening parameter for primary photocurrent. c_{IB} as a potential screening parameter was unexpected since it was assumed that the junction areas were nearly constant for a given device type. However, c_{IB} is dependent upon the base doping concentration near the e-b junction and, thus could reflect a large gradient in base impurity doping concentration. The electric field produced by this gradient would enhance the carrier flow to the c-b junction and the subsequent photocurrent. The correlation with t_{B} is reduced by the presence of an internal electric field.

Since no single screening parameter appeared to be successful as a primary photocurrent screen, multiple linear regression (MLR) analyses were performed using the parameters predicted to be effective from theoretical reasons as well as those the data indicated were correlated to I pp. These results (summarized in Table 56) were, in general, disappointing and while effective in reducing the prediction errors, were not sufficiently effective to implement as a screening technique.

b. Secondary Photocurrents

Secondary photocurrents, I_{sp} , were measured in a grounded base configuration. The main "turn-on" mechanism for this case is the transverse voltage generated by the IR drop of the primary photocurrent and transverse base resistance. This model (presented in Paragraph 3-b, Section V, Volume 1) predicts that the following parameters are important for screening I_{sp} :

- 1. I_{pp} (and parameters for which I_{pp} is dependent),
- 2. r_R, transverse base resistance,
- 3. $h_{\mbox{\scriptsize FE}}$, common-emitter DC current gain,
- 4. $N_{\mbox{\scriptsize RO}}$, base region impurity doping concentration, and
- 5. t_B , base transit time.

In general, the correlations for I_{sp} were much better than for I_{pp} . A summary of the correlation coefficient for potential I_{sp} screening parameters are shown in Table 57.

POWER TRANSISTORS

a. Primary Photocurrent

Primary photocurrents for power devices, though considerably larger as a result of larger device geometries, do not differ in principle from those of low-power devices. However, power devices do exhibit greater tendencies for secondary effects such as the onset of "anomalous" photocurrents due to transverse effects enhanced by their larger photocurrents and geometries.

An inspection of a histogram of I pp for the RCA TA8007 in Figure 58 shows seven devices which exhibited these anomalous I seven at rates as low as 3.0 x 10 7 rad(Si)/s. Two are shown on the histogram and the other five had such large I so that they are shown as outside the range of the histogram. These devices all had low values of base doping concentration N $_{\rm BO}$. The mean values of the doping level for all devices was $^{\rm 5.6}$ x 10 16 cm $^{\rm -3}$, while the devices which exhibited anomalous turn-on all had values $^{\rm -2}$ x 10 16 cm $^{\rm -3}$. This result is apparent in scatter diagrams of I versus N $_{\rm BO}$ and r $_{\rm B}$ (Figures 59 and 60).

b. Secondary Photocurrent, I sp, and Turn-on Threshold

The radiation rate threshold for I_{sp} "turn-on" varied nearly a factor of 25 for the TA8007 and nearly a factor of 4 for the BR200A. These ranges can be seen in the histograms shown on Figures 61 and 62. Based on a simple analytical description for I_{sp} , the key parameters for screening I_{sp} are: (1) h_{FE} , (2) r_{B} , and (3) I_{pp} .

The scatter diagrams in Figures 63 through 66 show the strong correlation between turn-on threshold and both h_{FE} and r_{B} . Thus, where transient photocurrents constitute the major failure threat, screens on high h_{FE} and r_{B} values would significantly truncate those failures which occur at the lower rates.

4. DUAL JUNCTION FIELD EFFECT TRANSISTOR

Primary photocurrent was measured at three dose rates for the dual JFET. The experimental arrangement was similar to that used for the bipolar transistors with the collector-base junction being replaced by the channel-gate junction. Source and drain were shorted together in this measurement and 30V was applied across the gate-channel junction.

Figure 67 shows the response (I $_{pp}$) as a function of dose rate, $\dot{\gamma}$, for the sample. In this plot the "A" and "B" halves are both shown.

We can see that the primary photocurrent is super-linear over the range of $\dot{\gamma}$ which was used. Therefore, photocurrent is following a relationship

$$I_{pp} = A_{\gamma}^{*n} \tag{13}$$

where n > 1. For the mean of our sample n was found to be ~1.2.

This super-linearity is expected due to two-dimensional mechanisms and the fact that the reverse bias was relatively near the breakdown voltage of the gate-channel junction (BV $_{\rm GSS}$).

a. Correlation Parameters

Parameters which are expected to correlate with I are: the reverse recovery time of the gate-channel diode, t $_{rrGS},$ the storage time constant, τ_S , defined as

$$t_{rrGS} = \tau_{S} \ln \left(1 + \frac{I_{F}}{I_{R}}\right)$$
 (14)

and the width of the depletion region which is inversely proportional to the depletion capacitance. It was expected that the lifetime measurements would correlate positively with I and that the capacitance would correlate negatively with I pp.

Table 58 shows a summary of rank correlation coefficients for the various parameters of interest. The parts have been divided into two groups labeled α and β ; group α contains serial numbers 1-35, and

group ß contains serial numbers 36-60. The reason for this grouping is that the two groups seem to come from different wafers or diffusions. Histograms of many of the electrical parameters appear as bimodal distributions with the groups appearing as two separate distributions. Hence, when a rank correlation is performed between two parameters which are each bimodally distributted, the correlation may be artifically high because of the separation of the two groups. This is shown by Figure 68 which shows a scatter diagram C_{GSS} (IV) versus I_{pp} [$\dot{\gamma}$ = 1.2 x 10 rad(Si)/s]. One can see from this plot and Table 58 that the rank correlation of the total (0.738) is high and that the correlation with capacitance within each group is significantly lower.

It is apparent from Table 58 that the best correlations were obtained with the parameters which are a function of lifetime. The storage time constant, τ_S , in general correlates as well or better than the reverse recovery time, and it appears that this parameter is the most likely candidate for a screening parameter for primary photocurrent. Note that there is a marked difference in the correlations between I_{pp} and τ_S observed in the two subgroups. The α subgroup data correlates much better than the β subgroup. This is, perhaps, more apparent in Figure 69 which shows a scatter diagram of the "A" chips.

b. Multiple Linear Regression Analyses

Multiple linear regression techniques were used to predict primary photocurrent using the correlation parameters discussed in the preceding section. Since the JFETs were apparently grouped into two subgroups, which implied that the parts came from either two wafers or diffusions, this allowed a measure of the predictive ability of the regression coefficients of the MLR parameters. For this to be the case, the independent variables used in the regression must be variables which physically describe the dependent variable. Were this not the case, the MLR coefficients would fit the data for which the coefficients were generated, but would not accurately fit another set of parts with slightly different physical properties.

MLR's were therefore run using t $_{rrGS}$, $_{S}$ and $_{GSS}$ and functions of these parameters. Table 59 summarizes the results of these analyses. We can see from this table that MLR techniques do not work well for the prediction of the response of devices with electrical parameters much different than those of the devices from which the MLR coefficients were generated unless the independent variables are theoretically plausible. The first two sets of MLR's shown used independent variables related to $_{pp}$ but with a meaningless functional relationship. Hence, the prediction errors are large. The third run, however, used $_{S}$ and $_{S}$ which are expected to be related to $_{pp}$ and, as expected, the regression works well. As Figure 69 showed in the previous material (Paragraph 4-b) the groups ($_{S}$ and $_{S}$) show quite different degrees of correlation with $_{S}$. The addition of the capacitance term, however, allowed a much better estimate of $_{S}$ than obtained with $_{S}$ alone.

c. Conclusion

As would be expected lifetime measurements give the best correlation and prediction for ${\tt I}_{\tt pp}$ in the dual JFET. Therefore, an MLR technique or an electrical screen using t $_{\tt rrGS}$ or several values of t $_{\tt rrGS}$ to give a fitted value of ${\tt T}_{\tt S}$ should provide the best HA screen for devices of this type.

5. INTEGRATED CIRCUITS

The transient ionization response of the integrated circuits was measured with direct exposure to 10 MeV electrons from a linear accelerator. The pulse width used was sufficiently wide to assure time equilibrium, and pulse widths ranged from approximately 100 ns for the TTL devices to 3 µs for the op amp. The decision to use a wide radiation pulse was reached because of the difficulty of measuring the response of fast circuits to narrow pulses and because of the more universal applicability of hardness assurance data obtained with wide radiation pulses, i.e., if the circuit is hard to a pulse width sufficient for time equilibrium, it is generally hard for any pulse width. Extreme care was taken to assure repeatability in the transient ionization measurements. Threshold response data was in general repeatable to better than ±5% relative

accuracy. Because this type of experimentation forces continual adjustments of the radiation intensity, it is very time consuming, and to minimize the expenditure of effort data was not taken for all sections of multiple devices. Additional general information on the experimental procedures is given in Paragraph 4-c, Section IV, Volume 1.

a. TTL Circuits

(1) Failure Criteria

The TTL circuits were loaded with a resistor-diode network that simulated maximum fanout for both logic states. The loading conditions for the 1-state are particularly important when measuring the ionization response because this causes the pull-up transistor to be in the active region which minimizes the output transient. In general, the failure criterion used for either logic state for these circuits was a 100 mV transient voltage shift at the output terminal, i.e., the failure criterion was equivalent to a 100 mV reduction in the allowable noise margin. This seems low, but it is the typical fraction of the normal 400 mV noise margin which is relinquished by the system designers for transient radiation. Most of the available noise margin is usually required for normal electrical design purposes. Since these circuits fail in either state because of secondary photocurrent in internal transistors, the radiation response is strongly nonlinear with dose rate, and moderate differences in response criteria will cause only slight differences in the radiation level for transient failure. One practical difficulty which arose during the 1-state tests was the stability of the power supply voltage. The $10~\mu f$ capacitor placed close to the device to bypass the power supply leads still allowed V_{CC} to change by as much as several hundred millivolts. This in turn affected the 1-state output voltage. To solve this problem, it was necessary to place a large (4000 μf) capacitor a few feet away from the experiment, out of the radiation beam. the supply voltage to within 20 mV during the transient pulse.

The transient voltage shift was used as a failure criterion instead of the absolute DC output voltage because: (1) it was experimentally more convenient to measure a consistent pulse amplitude, (2) failure mechanisms involving secondary photocurrent are likely to be more

consistent from unit to unit, and (3) circuits which have DC logic levels close to the worst-case values for these parameters will fail with transient output voltages of a few hundred millivolts.

(2) Failure Mechanisms

The expected failure mechanism for the 1-state response of the TTL devices is turn-on of the output transistor. Obvious correlation parameters for secondary photocurrent are the h_{FE} and r_{B} of the output transistor and the value of the external base resistance. Storage time, capacitance and stored charge were expected to correlate with primary photocurrent.

The expected failure mechanism for the 0-state is turn-on of the pull-up transistor. One obvious correlation parameter is the value of the external base resistance. For all of the TI circuits except the inverter, this resistor was significantly lower than for the corresponding circuits made by Motorola (1K Ω versus 4K Ω for the standard gate). Because the secondary photocurrent of the pull-up transistor may cause transient increase in the $V_{\text{CE}(\text{SAT})}$ of the output transistor, the dynamic resistance of the circuit in the 0-state is also important.

(3) Radiation Data

Transient radiation data for the five TTL device types were taken for approximately 140 units of each type. The sample histogram of the data in Figure 70 shows the transient threshold data for the TI inverter (1-state). The data for all of the device types is summarized in Table 60, which lists the mean, standard deviation, ratio of maximum to minimum value, and worst or most radiation sensitive value. This is simply a tabular presentation of the radiation data which allows the reader to make a comparison of the data for different device types and different test conditions. Since the data for the TI buffer has a maximum to minimum ratio of only 2, one can anticipate more difficulty in obtaining high rank correlation coefficients for this device.

The limited spread in the radiation data for most of these devices was a major limitation in investigating the effectiveness of various electrical parameters in screening the radiation response distributions. The parts had already been through a stringent selection procedure

because of the electrical specifications and processing controls which were included in the parts specifications. This is probably the reason that the AC and switching measurements were relatively ineffective. Any device with extreme AC parameters had already been eliminated. Another aspect is that the basic resolution and accuracy of these AC measurements are significantly lower than those of the DC parameters and hence, these measurements would be expected to be less effective in correlations with tightly grouped radiation data. An alternative approach would have been to deliberately allow some fraction of the devices in the test population to be out of tolerance. This would have broadened the range of the electrical parameters, and made it easier to assess correlation effectiveness. However, this approach would also raise a question about the applicability to practical groups of devices which do undergo a stringent initial electrical screen.

In the following material, it is apparent that the results are best for devices which have a wide spread in radiation parameters. The relative accuracy of the radiation dosimetry and the electrical measurements are less important for devices with wide spreads in radiation behavior. In most applications, a range of 3 to 4 in the spread of radiation behavior would be acceptable, and there would be no need to apply techniques to further truncate the distribution. The main goal of hardness assurance is to eliminate devices from one end of the distribution, and it is difficult to accomplish this goal if the sample of parts used do not have sufficient variability.

(4) TI Inverter

Some interesting results were obtained for the TI inverter 1-state response. High rank correlations were obtained for h_{FE} , as shown in Table 61. However, when h_{FE} was applied as a screening parameter, eliminating devices with highest h_{FE} values, "wo devices stubbornly persisted in the lower, more radiation sensitive, side of the histogram, and it was apparent that, in spite of the high correlation coefficient, h_{FE} was not working well as a single correlation parameter. The electrical parameters of the two devices were examined in more detail, and it was found that both devices had abnormal values of ${\rm V}_{\rm OH}$, one being very high,

the other very low - in fact, the low device was just beneath the 2.4V specification limit. The reason for the high V_{OH} reading was an open internal resistor. This same problem occurred for one of the Motorola circuits, and is further discussed in Paragraph 5-b of this Section. When V_{OH} was included as a screening parameter, the results shown in Figure 71 were obtained. These results suggest that abnormal device behavior, in spite of electrical test limits, can still affect radiation behavior, and support the concept of monitoring a wide number of device parameters to achieve hardness assurance. The significance of V_{OH} as a parameter for electrical evaluation of TTL circuits is discussed in detail in Paragraph 5-b of this Section. These results show that radiation hardness can be improved by monitoring appropriate data, adding additional tests, and imposing tighter limits for some parameters. The existing limits in the Honeywell specification were not sufficient for this purpose.

A further interesting result was obtained for the TI inverter. Returning to Figure 71, one device is conspicuously located on the leading edge of the histogram even after the $h_{\rm FE}$ and $V_{\rm OH}$ screens were applied. This device had the highest value of propagation delay time, and this value was significantly greater than that of any of the other devices. This is one of the few examples of successful application of switching parameters for the TTL ICs. Conversations with Honeywell at the beginning of this program yielded the information that both manufacturers were having difficulty meeting the switching time specifications for these parts, and this had a major effect on device yields. Certainly, as discussed in Paragraph 3-b, Section IV, Volume 1, storage time is an expected correlation parameter for primary photocurrent, and the fact that measurements affected by storage time were of limited success in this program is probably due to the stringent selection imposed by the vendors in meeting the Honeywell specifications. For more loosely processed parts, theory and the results for the TI inverter support the inclusion of switching times in any hardness assurance program.

(5) TI Buffer

The TI buffer was the only digital circuit which used primary photocurrent compensation. The LINAC test results revealed that this compensation was not completely effective. For a 100 mV transient output response, the uncompensated Motorola buffer was actually harder. However, for higher transient voltage shifts, the compensation worked reasonably well; the dependence of output voltage on dose rate was much less sharp for the TI buffer than for any of the other TTL circuits. For this reason, the responses at a fixed rate could be used to compare different units of this circuit.

The range of responses for the TI buffer was only a factor of 2, and because of the limited range and the compensation, it was difficult to find good correlation parameters for this circuit. Nevertheless, for higher output responses, a single correlation parameter, $V_{\rm CS}$, was found which was reasonably successful. Figure 72 shows a histogram of the output responses, with the high and low offset voltage units eliminated from the distribution. This parameter, which is expected to correlate with lifetime, was successful in eliminating the worst units from the already narrow histogram. Considering the fact that this is a compensated circuit, the results are quite promising. The rank correlation factors of several parameters of interest are summarized in Table 62.

(6) TI A-O-I Gate

The TI A-O-I gate was selected because it contains two phase splitter transistors which are connected in parallel. The increased photocurrent in the common collector resistor of the phase splitter transistors makes these circuits more sensitive to ionizing radiation than the simple gates, which have only a single phase splitter transistor. No abnormal $V_{\rm OH}$ values were observed for any of the A-O-I gates.

Rank correlation coefficients for these devices are summarized in Table 63. There were no parameters with high rank correlation coefficients for this device type. However, the results of an MLR run, shown in Table 64, show a relatively low rms error of 16%, and a maximum error of only 45% when 5 parameters are used to obtain MLR coefficients.

As with all the MLR runs for the ICs, the first half of the devices were used to obtain the MLR coefficients and the radiation response of its entire population was predicted using these coefficients. The rms and maximum errors apply to the prediction of all units.

(7) Motorola Inverter

The Motorola inverter population also had two devices with abnormal V_{OH} behavior, and the radiation thresholds of these units were also abnormally low. One of these devices had extremely high leakage current, and although it passed the vendor's electrical tests, would not have passed an additional 100% test by the user because the I_{OL} measurement was "out of spec". However, even though the other device met all specifications, curve tracer tests revealed that the cause of the high V_{OH} value for this unit was that R_3 , the resistor from the base of the output transistor, was open.' This greatly increased the sensitivity of the device to transient radiation. A more detailed discussion of the cause and significance of abnormal V_{OH} values, along with suggestions for eliminating this problem with additional electrical tests, is included in Paragraph 5-b of this Section.

Rank correlation coefficients between several electrical parameters of the Motorola inverter and the ionization threshold are listed in Table 65. Once the two abnormal devices were identified, the range of the ionization response data was reduced an order of magnitude. The results of two MLR computer runs are shown in Table 66. The first run includes all devices; the second run was generated with the two abnormal devices removed. The first MLR run had an rms error in excess of 100%, and the maximum error is even higher. However, when the two devices were removed, large reductions in the rms and maximum errors were obtained. This example illustrates the significant effect of a small number of abnormal devices or bad data points on the results of an MLR calculation. High quality data must be used in order to obtain reasonable results with multiple linear regression.

(8) Motorola Buffer

Results for the Motorola buffer were better for the O-state than the 1-state. Unfortunately, the 1-state is the more sensitive of the two states. Rank correlation coefficients of various electrical parameters vs. ionization response are shown in Table 67. However, an examination of the 1-state data, presented in Figure 73, shows that the data is already well truncated on the lower, more radiation sensitive side. Except for one device, the minimum values are only a factor of 2 below the mean value of the distribution. With this type of histogram, low rank correlations are expected because of the large peak on the low side. Slight errors or "noise" in either the radiation or electrical data will cause large rank differences in such a skewed distribution. When this is considered, the result for the Motorola buffer are not unreasonable. Regression techniques were also applied for the Motorola buffer, and these results are presented in Table 58. Again, the 0-state results are better than the results for the 1-state, but the wider range of the 1-state data at the high end would be expected to affect the MLR results for this case.

b. The Effect of Resistor Reliability on Radiation Response

(1) Open Resistor Problem

One extremely soft device was found in each group of inverters from the two manufacturers. The only significant difference in the electrical behavior of these two devices was a slightly higher value of V_{OH} . Additional measurements, which were made on these devices with a curve tracer, proved conclusively that the high V_{OH} readings were caused by an open R_3 resistor from the base of the output transistor to ground (see Figure 74). This also explains the extreme sensitivity of these particular devices to ionizing radiation.

After identifying this problem, it is disquieting to realize that these parts still meet all electrical specifications, in spite of the open resistor. Similar devices could easily be installed in "radiation-hard" systems, and would lower the transient failure level of such systems by more than one order of magnitude. In the following section, we will

discuss the means of detecting this problem and implementing tighter electrical specifications to screen this fault at the vendor or at an incoming inspection level.

(2) Method of Detecting Open Base-Emitter Resistors

The Von readings for the two faulty devices were approximately 300 mV higher than the average value of 2.7V which occurs when $V_{CC} = 4.5V$ and $V_{IN} = 0.8V$ for the inverters. There are several factors which can cause $V_{\mbox{OH}}$ to be high, but the distribution of $V_{\mbox{OH}}$ readings for normal devices is tightly grouped around 2.7V with a total spread of less than 100 mV. High V_{OH} readings can be caused by the following conditions: (1) high leakage in the output transistor, (2) an open R_{λ} , (3) an open R_3 , or (4) a short between base and emitter of Q_3 or Q_4 (see Figure 74 for a circuit schematic). Condition (3), R_3 open, can be verifield by examining the V-I characteristics of the 1-state output as the input voltage is changed from 0.4 to 1.2 volts. In normal devices, the output voltage will change approximately 300 mV as the input voltage is changed from 0.4 to 0.8V. This is caused by the phase splitter transistor turning on, because of the inverted saturation of Q_1 . In order for the phase splitter to turn on with 0.8V applied to the input, R_3 must be present. If R_q is open, the phase splitter and the output transistor will turn on simultaneously at input voltages above 1V but there will be no change in 1-state output voltage until the input level exceeds 1V. The output V-I characteristics of a normal device and a device with R, open are shown in Figure 74.

Another resistor which could be open, and still allow the circuit to pass electrical specifications is R_4 . This would greatly increase the sensitivity of the circuit in the 0-state, because Q_4 effectively has an open base if R_4 is open. This particular problem was not observed on any of the devices in this program, but is nevertheless an important consideration given the incidence of open R_3 resistors encountered in these devices. The other resistors $(R_1,\,R_2\,$ and $R_5)$ are all necessary for proper circuit operation, and the circuit would not pass electrical or functional tests unless these resistors are connected properly within the circuit.

(3) Electrical Screening Methods

One screening method for the presence of R_3 is simply to put a maximum as well as a minimum value on $V_{\rm OH}$. The maximum value could be assigned as 2.85V with $V_{\rm CC}$ = 4.5V and $V_{\rm IN}$ = 0.8V, which would eliminate this particular problem for devices with the pull-down resistor connected to ground. The limit would have to be adjusted upwards for devices which use a pull-down resistor across the base-emitter junction of Q_4 , which is typical of all the TI devices except the inverter. For circuits with different resistor values, such as the buffers, slightly different values of $V_{\rm OH}$ may be required.

For complex MSI circuits, it may be impossible to verify proper resistor connections for points buried within the circuit from measurements with the external leads. There are two approaches to this problem. One is to improve resistor reliability so that resistor contact failures will have a very low probability of occurring. Based on our results, the present technology has not solved this problem. An alternative approach is to measure critical internal $V_{\mbox{OH}}$ values with extra pads during the wafer probing, or the resistor could be measured directly. This approach assumes that the resistor reliability problem is not affected by the die bond, packaging and burn-in. This is probably a poor assumption, because of the high temperatures which occur during the die bonding and electrical stress caused by burn-in procedures.

(4) Conclusions and Recommendations

We have discovered circuits with open internal resistors which are much more sensitive to ionizing radiation than normal circuits. Users of hardened circuits should be aware that this problem does not occur with sufficient regularity to be discovered with the typical sample testing that is done to evaluate hardened parts, but does occur often enough to seriously effect system hardness. Techniques for screening such devices with tighter V_{OH} measurement limits have been suggested, and it is recommended that these methods be applied to eliminate these bad devices. Additional effort should also be made to solve the problem at the manufacturing level.

c. Other Integrated Circuits

This section presents the ionization results of the TI word switch, Motorola sense amplifier and Fairchild ν A744 operational amplifier. The ionization test results are summarized in Table 69, which shows the mean value and range of the ionization response data for each of these devices.

(1) TI Word Switch

The primary photocurrent and the radiation threshold for a secondary photocurrent of 200 mA were used as radiation response criteria for the word switch. The ionization response data were very tightly grouped, with a ratio of maximum to minimum value of about 1.5 for both the I s and the response thresholds. Considering the estimated relative inaccuracy of the dosimetry, which could be as high as 5%, correlation factors would be expected to be somewhat worse for the word switch than for devices with higher spreads in radiation data. A table of rank correlation coefficients for I and the I sp threshold is shown in Table 70.

Although the distributions of I_{pp} and I_{sp} were narrow, the increased flexibility of measurements with the word switch resulted in good screening parameters for I_{sp} . Figure 75 shows a histogram of the initial data, and also shows the improvement after using h_{FE} and the external base-emitter resistance value as screening parameters. Storage time also worked as a screening parameter for this circuit. Since the initial histogram was already very tight, with a steep lower side, it is encouraging that the application of these relatively simple parameters (see Paragraph 3-b, Section V, Volume 1 for a theoretical discussion) further narrows the distribution.

A multiple linear regression run was also made to see how well the word switch turn-on threshold could be predicted. The results, shown in Table 71, have an rms prediction error of 3.9% with a maximum prediction error of 11.5%. These were the best MLR results obtained for any of the integrated circuits, and the success of the realits for the word switch is probably due to the increased flexibility of measurements which are possible when the output transistor is accessible.

(2) Motorola Sense Amplifier

Radiation testing of the Motorola sense amplifier was complicated by the wide variations in offset voltage between units, which was further aggravated by the fact that the offset voltage specification was relaxed in order to obtain the devices on a reasonable schedule. The first stage of a plated-wire sense amp always operates in a linear, nonsaturating mode, and the offset voltage problem was resolved by operating the devices at a fixed output voltage of 1.5 volts. This is the center of the operating characteristics of the typical logic gate which would be driven by the sense amp. The radiation failure criterion was that a 3 mV differential input signal from the pulse generator would no longer drive the output beyond the TTL noise margin limits of 0.4 or 2.4 volts during the radiation pulse. The 1.5 volt operating level was achieved by using an operational amplifier to provide the necessary input biasing voltage. The op amp was located in the data room in order to eliminate its radiation response, and a large frequency compensation capacitor was used to prevent the op amp from responding to the radiation transient. A diagram of this experimental arrangement is shown in Figure 76.

The sense amplifier is a complex circuit, and based on the range of offset voltages encountered for the 4-input channels, the internal transistors were not as well matched as the transistors in modern junction-isolated circuits. The internal mismatches in \boldsymbol{V}_{BE} are important in establishing bias currents in the various stages, and the mismatches in $V_{
m RE}$ make it unlikely that external measurements will correlate with transient radiation behavior. The types of measurements which can be made are also severely restricted by the limited number of pins and fixed resistor values. An examination of the LINAC data showed that, although there was often a correlation between the data for different channels on the same device, there were also cases where large differences occurred between the channels on the same device. Rank correlations of several electrical parameters with the ionization response of the sense amplifiers are shown in Table 72. All of these correlation coefficients are very low, and are an indication of the difficulty of establishing good correlation parameters for this device. The MLR approach was also unsuccessful, as can be seen from the results listed in Table 73.

(3) Fairchild Operational Amplifier - µA744

As mentioned previously in (Paragraph 2-b, Section IV, Volume 1), the Fairchild μ A744 is a radiation hardened, dielectrically isolated operational amplifier which is <u>not</u> gold doped. Therefore, this device exhibits long radiation storage time once saturation occurs, and also is more sensitive to ionizing radiation than some of the newer hardened op amps which are gold doped. Three different ionization response measurements were made on this circuit, (1) the output voltage response at 4.3×10^6 rad(Si)/s. (2) the radiation level required to just saturate the circuit, and (3) the radiation recovery (storage) time at 9×10^8 rad(Si)/s. For these tests, the circuit was connected as an inverting voltage amplifier with a gain of 10. Power supply voltages were ±12 volts.

The rank correlations of several electrical parameters with the radiation responses are summarized in Table 74. As expected, the electrical saturation recovery time was one of the best correlation parameters (see Paragraph 3-b, Section V, Volume 1). However, because of the complex behavior of this device, no single parameter worked very well in screening the more sensitive devices. For the high transient response at the edge of this saturation threshold, the electrical saturation recovery was a good correlation parameter. A multiple linear regression run was made to compare this approach with the single parameter approach. These results are listed in Table 75, and are not particularly good. The five units with the highest low-level response were not screened by either the single parameter screen or the MLR approach.

These results indicate that complex linear circuits will be difficult to handle when measurements are restricted to those possible with external leads. It would be interesting to examine the feasibility of breakout transistor measurements as screening parameters for the ionization response of linear circuits. This would certainly increase the flexibility of measurements, although both pnp and npn transistor types would have to be made available.

d. Summary and Conclusions

The most significant result of the ionization response study on ICs was the discovery that open internal resistors occurred for devices from two manufacturers, which increased the radiation sensitivity of these devices by approximately one order of magnitude. Electrical screening procedures were developed which will screen such devices with tighter limits on one electrical parameter for TTL small scale integrated (SSI) circuits.

The normal ionizing rate response data of most of the devices were tightly grouped. Because of this narrow range of data, the uncertainty in dosimetry and the small errors in electrical measurements tended to obscure fundamental correlations. The electrical measurement problem was further complicated by the fact that the ICs were procured to a rigid set of specifications which screened out devices with extreme electrical behavior and narrowed the distribution of electrical parameters. This magnified the effect of the errors and resolution limits in the electrical measurements.

In spite of the narrow distributions, correlation and screening parameters were found which further truncated the already narrow distribution. In general, the results were best for circuits which allowed a reasonable inference of internal transistor parameters from external measurements. For very complex circuits, with limited access to internal transistor parameters, such as the sense amp and op amp, results were considerably worse.

6. MTBF RESULTS FOR PARTS SUBJECTED TO IONIZING RATE TESTS

Although the general applicability of a gamma-rate screen was not a part of this program, it was felt that MTBF testing of parts subjected to high dose rate environments would yield results of immediate applicability to some military systems. To this end a group of inverters and buffers were submitted to life testing after exposure to the ionizing rate tests. Neither catastrophic nor drift failures were observed in the exposed group of 49 inverters although the control group (99 parts) showed three failures, 2 catastrophic and 1 drift. For the buffers, 2 drift and 1 catastrophic failure were observed out of the exposed group of

48, although the control group of 94 parts showed no failures of either kind. Converting the catastrophic failure numbers to failure rates at a 60% confidence level results in Table 76.

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Figure 49. Histogram of Primary Photocurrents at 5.3 x 10⁸ rad(Si)/s for 2N696

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Figure 50. Histogram of Primary Photocurrents at 1.35 \times 10^{10} rad(Si)/s for 2N2222

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Figure 51. Histogram of Primary Photocurrents at $6.0 \times 10^9 \, \mathrm{rad}(\mathrm{Si})/\mathrm{s}$ for $2\mathrm{N}2905\mathrm{A}$

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Figure 52. Histogram of Primary Photocurrents at 6.0 x 10^{10} rad(Si)/s for 2N3960

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Figure 53. Histogram of Primary Photocurrents at 8.0 \times 10¹⁰ rad(Si)/s for 2N709

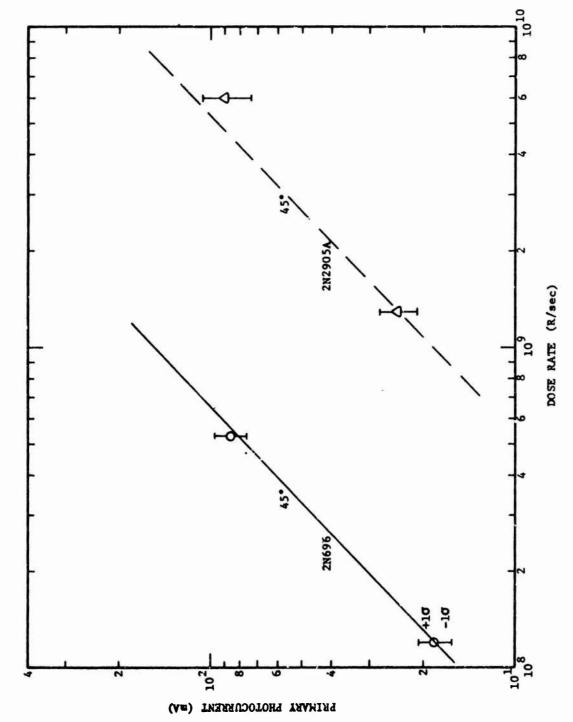
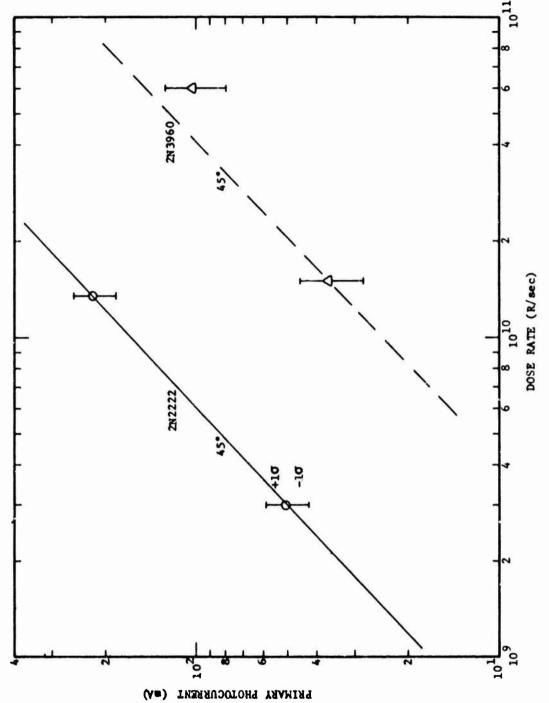
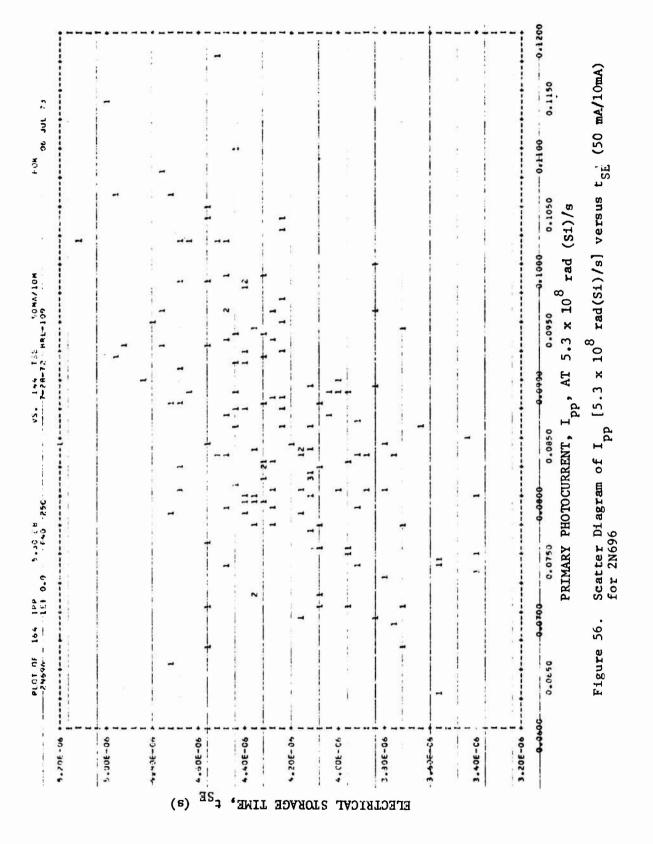
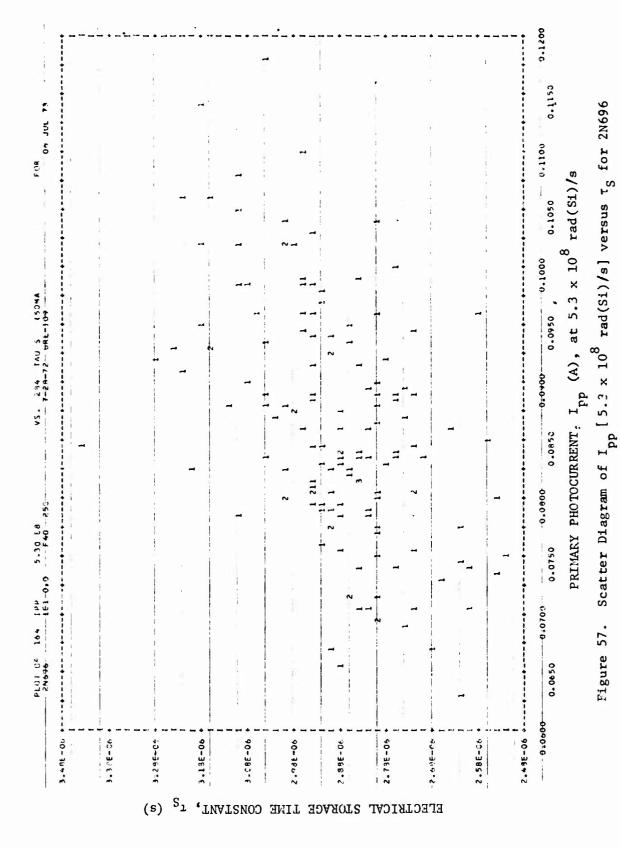


Figure 54. Dose Rate Dependence of Mean Primary Photocurrent for 2N695 and 2N2905A

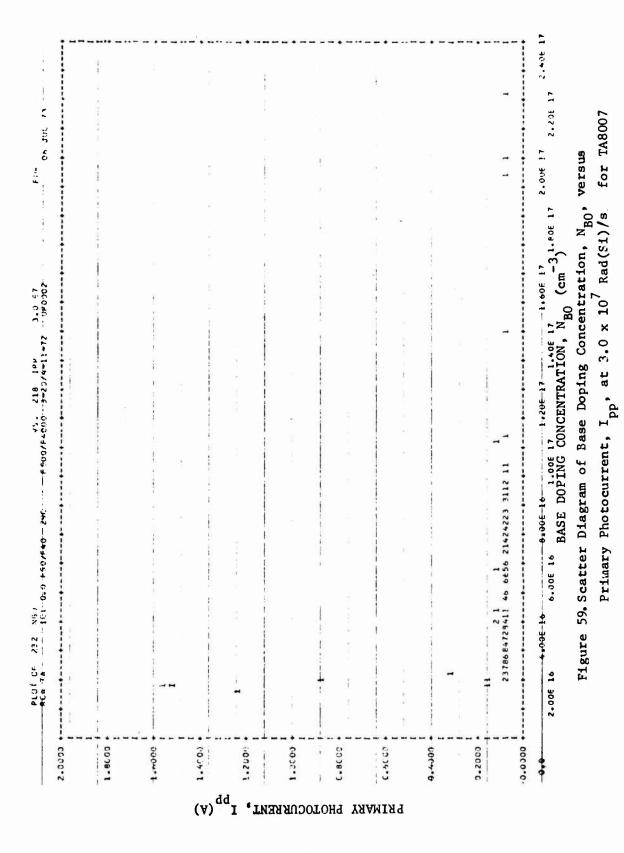


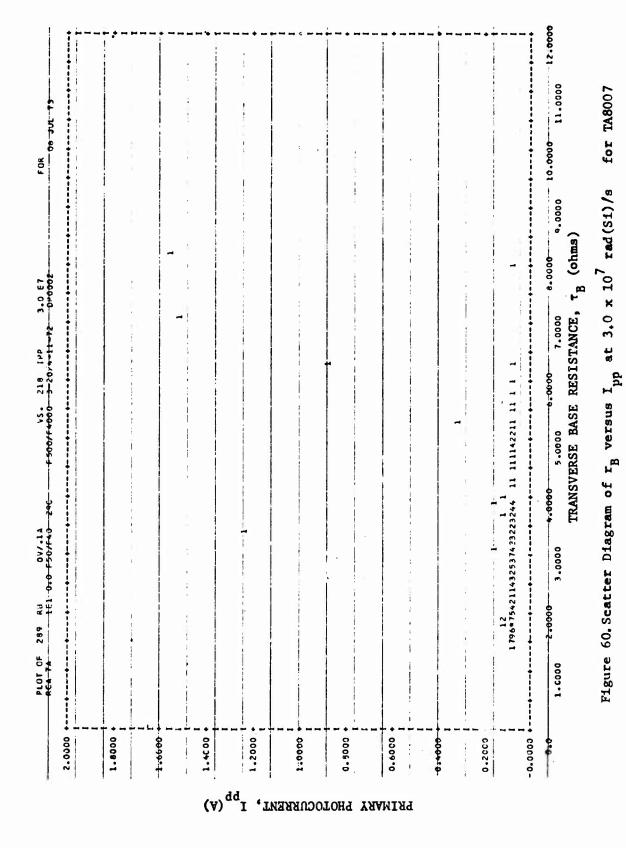




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Histogram of Ipp at 3.C x 10^7 rad(Si)/s for TA8007 Showing Devices with "Anomalous" Photocurrents Figure 58.





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Figure 61, Histogram of Threshold Rate for Turn-On (I $_{\rm Sp}$ = 2A) for RCA IA8007 in Shorted-base Configuration

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Figure 62. Histogram of Threshold Rate for Turn-on (I = 1A) for Solitron BR200A in Shorted-base Configuration

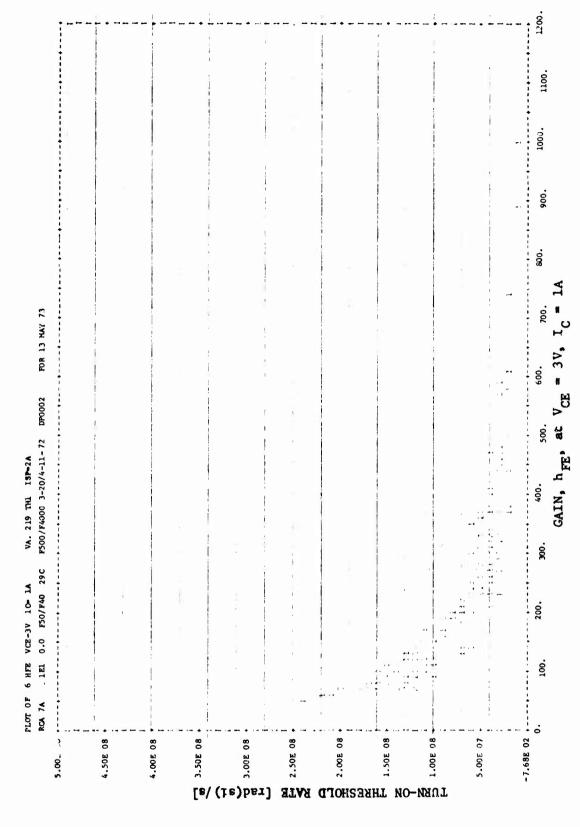


Figure 63. Scatter Diagram of hFE (3V/1A) versus Trun-On Threshold Rate for RCA TA8007

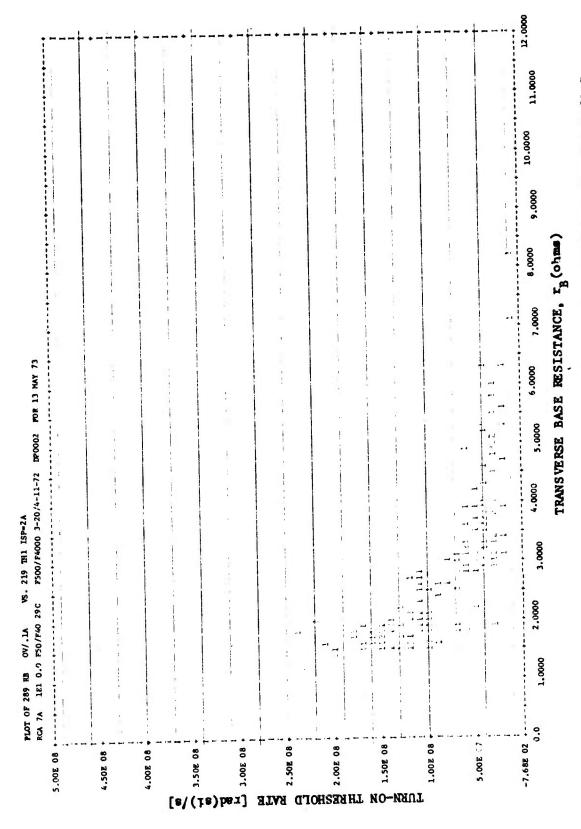
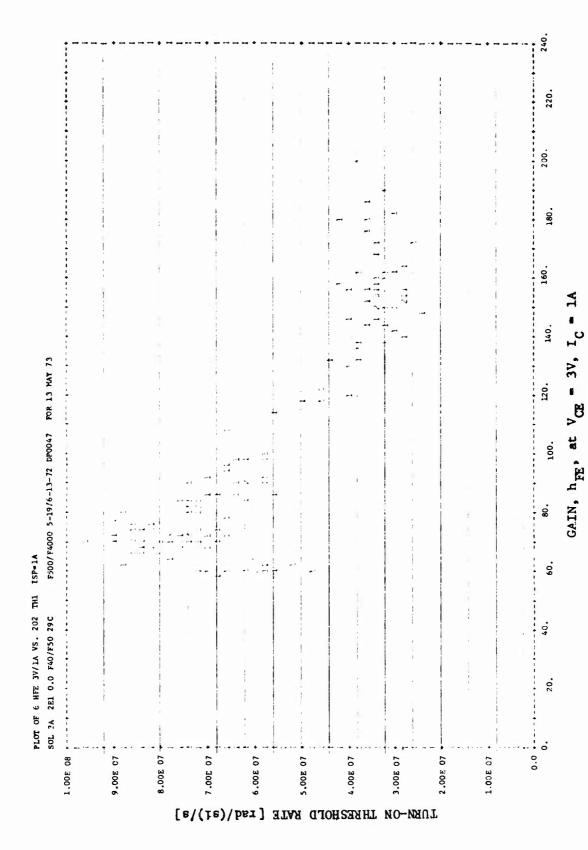


Figure 64. Scatter Diagram of rB versus Turn-On Threshold Rate for RCA TA8007



Scatter Diagram of $h_{\overline{FE}}$ (3V/1A) versus Turn-On Threshold Rate for Solitron BR200A

Hgure 65.

39

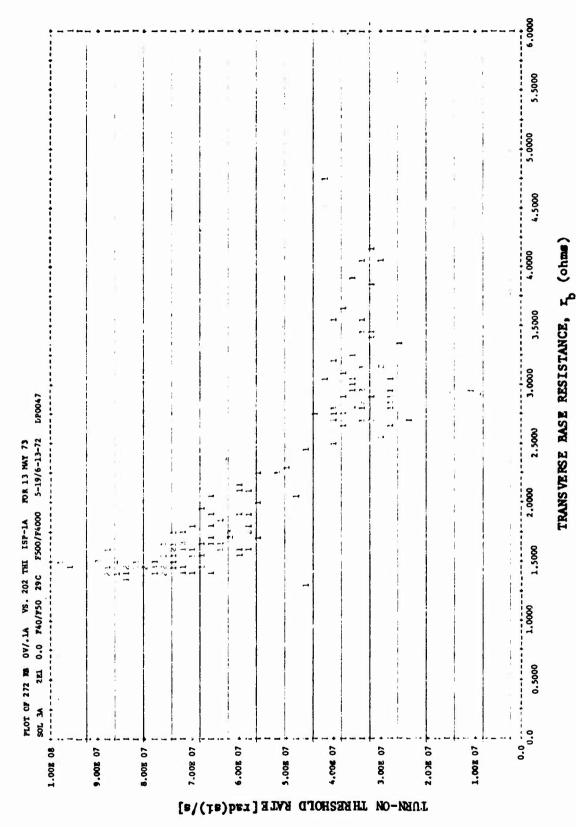


Figure 66. Scatter Diagram of r_B wersus Turn-On Threshold Rate for Solitron BR200A

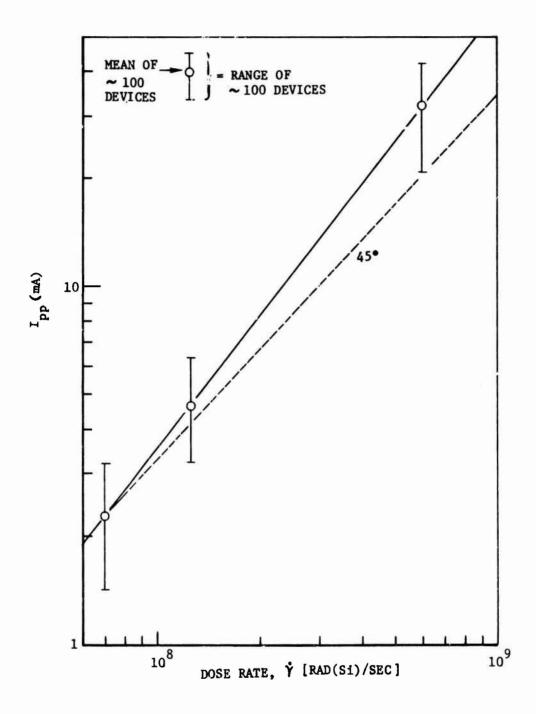
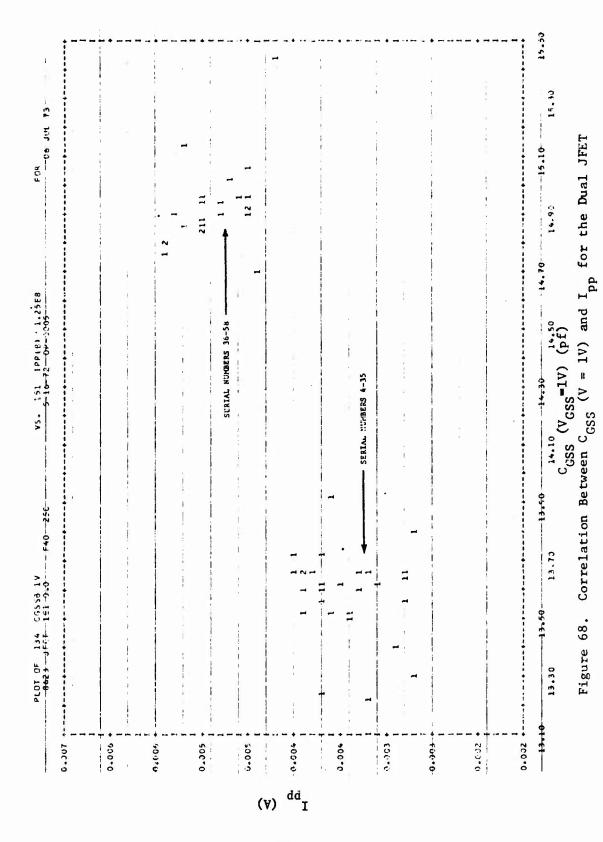
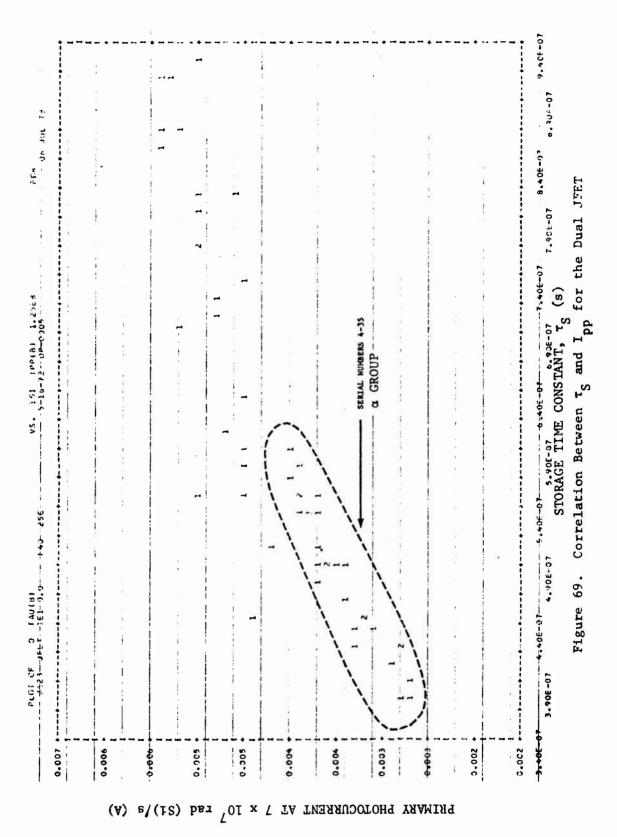


Figure 67. Superlinearity of Primary Photocurrent, I_{pp} as a Function of Dose Rate for the Dual JFET





0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.0	0.0 3.036 0.0 3.036 0.0 3.036 0.0 4.537 0.0 6.537 0.0 6.537 0.0 6.537 0.1 7.737 0.2 6.537 0.3 6.	1	367 133 069120115 363286135					
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A Sample Histogram of the Radiation Response Threshold Data (TI Inverter 1-State Response) Figure 70.

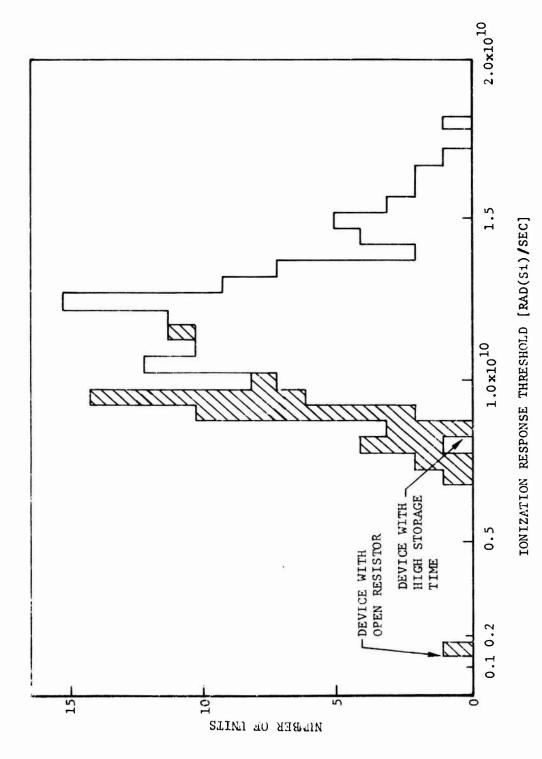


Figure 71. Histogram of TI Inverter 1-State Response Thresholds Showing Truncation With Electrical Storage Time

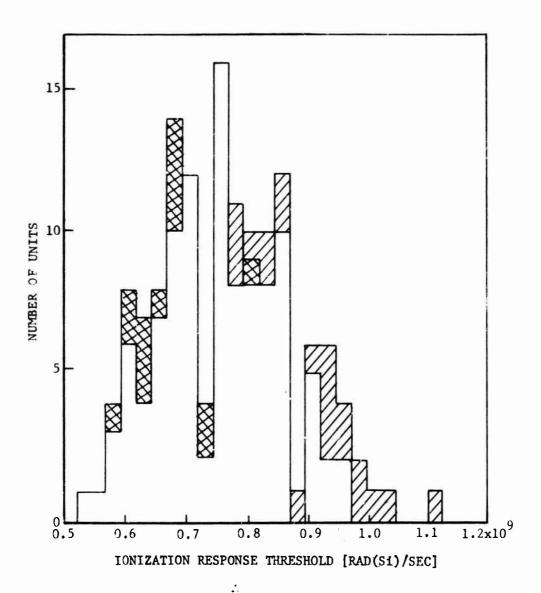
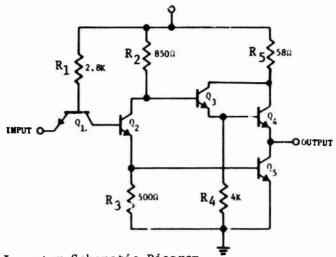


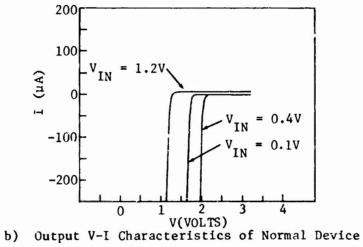
Figure 72. Truncation of TI Buffer Radiation Responses with Offset Voltage

### ### ### ### ### ### ### ### ### ##	040 102105 125126129130134135137138140141150 07507T021067104105107109110112115127131139142144147 07507T0210671041041051071091101121151151111111111111111111111111	11150 1211512713113 1311411611713	79142147 79137137197 91371974551	6.4		
6.000000000000000000000000000000000000	1301341351371381401 0671341061071391161 072273074644294 0473780747779625 0176430446456 01764304464567 113112113	11150 1211512713113 1311411611713333333333333333333333333333	9142144147	6.9		;
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	1301341351371381401 0672041061071091101 0720720720720720720 0720720720720720 017043044640035770 113120122 041720122	11150 1211512713113 1311411411711	913-142-147 913-146-145 913-146-145	6-4		
000046 400 400 400 400 600 600 600 600 6	1391341351371381401 0672341051071391161 67237367454504103 67375377774103 5836471777412 0176433446450535773 11316132 6417777	11150 2211512713113 2311411411711	9132144147			
244 4 4 4 4 4 4 4 4 4 4 4 4 4 4 6 4 6 4	1391341351371381401 0671341061071391161 (723730746346941031 0470430746746416 0176430466466173 113120132 (41170126	41150 4211512713113 5911411511711	9142144147			
4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4	1301341351371381401 0071341051071391101 0722730746346941031 072273074673697 017643046640636773 1131120132 011620132	41150 4211512719113 5911411611711 5303556608808	9132144147 91371346451 9137111122	6.4		
# CHARLES # # 4 4 4 4 6 6 6 6 6 6 6 6 6 6 6 6 6 6	1391341351371381401 0671041061071091101 067207207463464101 0720720746346794707 05304649083570 113120122 051545	41150 1211512713113 1311411511711 1302546508928	9132144147 91331361451 0103111122	0,4		
	0871041091071091101 C72073074C54C94C9 0876077794H2 087643044G450832770 113120122 C4177050	1211512713113 1311411611711 1302556666878	9142144147	6.4		
4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4	12.20.73.07.46.00.73.07.07.07.07.07.07.07.07.07.07.07.07.07.	302556604838	91311346451	6		
	03364210121124140 017043046490432770 119120122	0.000.000.000.000	72111126			
######################################	01704304464301720 117120132 0114120132 0114120132		1			í
	112120132 113120132 151452 151452	21.093.01123	-			
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	1410-161-16-18-18-18-18-18-18-18-18-18-18-18-18-18-					
2000 000 000 000 000 000 000 000 000 00	312 1.1 1.1 162r 334.317649355564					
4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	v,					
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.0						
0.00 1.00 1.00 0.00 0.00 0.00 0.00 0.00						
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3 3.3 2.3 6 03 .						
'>	2	10	·	0.2	52	30
	The same of the sa	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	;			

Figure 73. Histogram of Radiation Response Threshold Data (Motorola Buffer 1-State Response)



Inverter Schematic Diagram



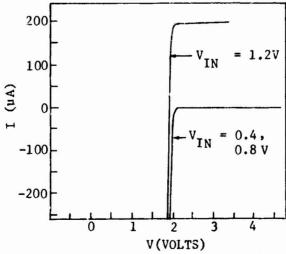


Figure 74. Method Used to Detect Open Internal Resistors in the Inverter Circuits

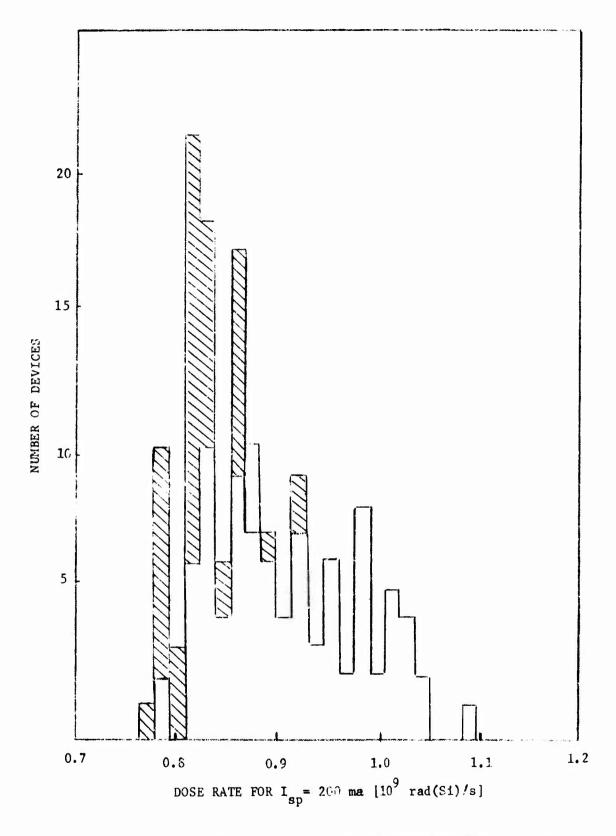


Figure 75. Truncation of the Word Switch Secondary Photocurrent Thresholds with \mathbf{h}_{FE} and \mathbf{r}_{B}

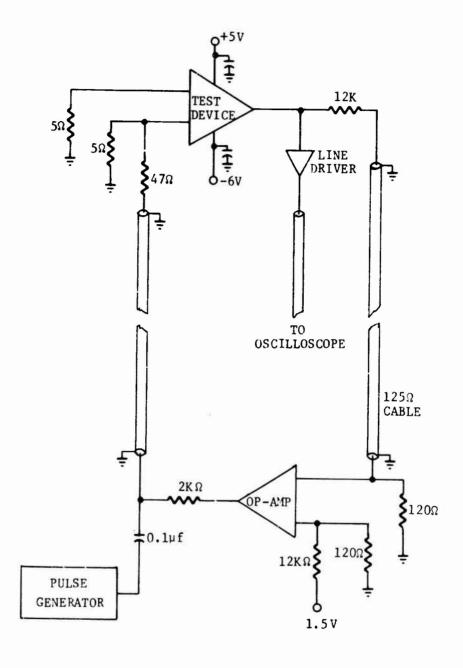


Figure 76. Experimental Method Used in LINAC Tests of the Motorola Sense Amplifier

Table 51 Summary of Low Power Transistors Tested for Transient Tonization Effects

Mfr.	Device Type	(a) Construction	Gold-Doped	Base Area	Approx. No. Parts Tested
FSC	2N696	NPN PE	No	3.43×10^{-3}	150
FSC	2N2222	NPN PE	No	8.47×10^{-4}	1 50
FSC	2N2905A	PNF	No	9.35×10^{-4}	150
FSC	2N709	NPN PE	Yes	3.65×10^{-5}	417
FSC	2N3960	NPN PE	No	3.65×10^{-5}	150
MOT	MT7111 Hez Inv.BOT	NPN PE IC Breakout (DI)	Yes	4.6×10^{-5}	30
мот	MT7113 Buffer BOT	NPN PE IC Breakout (DI)	Yes	3.03×10^{-4}	30
Tī	TI7111 Hex Inv BOT	NPN PE 3 IC Breakouts	Yes		87
TI	TI7113 Buffer BOT	NPN PE 3 IC Breakouts (DI)	Yes		87

⁽a) PE = Flanar Epitaxial(b) DI = Dielectric Isolation

Table 52 Summary of Photocurrent Data for Low-Power Transistors

		T V V V V V V V V V V V V V V V V V V V		H S I	Photocurrent		
Device Type	Response Mechanism	Rate [rad(S1/s]	Mean (mA)	Standard Dev. (mA)	Range (mA)	Max/Min	Normalized mA/[rad(S1)/s]
2N696	dd _I dd _I dsI	$ \begin{array}{c} 1.2 \times 10^8 \\ 5.3 \times 108 \\ 5.3 \times 10^9 \end{array} $	18.4 86.1 531	2.3 10.8 67.6	24.9 - 13.6 119 - 63.5 722 - 403	1.83 1.88 1.79	1.47×10^{-7} 1.62×10^{-7}
2N2222	rap qq1 qs1	3.0×10^9 1.4×10^{10} 1.4×10^{10}	50.7 220 668	8.2 34.9 201	65.3 - 29.4 290 - 143 1.08 - 369	2.22 2.02 2.93	1.69 × 10 ⁻⁸ 1.63 × 10 ⁻⁸
2N2905A	dd dd; dsI	1.3 x 109 6.0 x 109 6.0 x 109	24.4 90.2 226	3.4 16.6 88.5	31.7 - 15.4 135 - 60.6 383 - 40.5	2.06 2.22 9.46	1.88 × 10 ⁻⁸ 1.50 × 10 ⁻⁸
2N709	$_{\rm Isp}^{\rm Ipp}$	8.0×1010 8.0×1010	50.8	7.5	80.9 - 31.9 271 - 36.7	2.53	6.35 × 10 ⁻¹⁰
2N3960	dd Isp	1.5 x 1010 6.0 x 1010 6.0 x 1010	36.7 102.7 209.2	8.6 23.5 63.4	320* - 15.6 174 - 49.7 386 - 65.4	20.5* 3.5 5.90	2.44 × 10 ⁻⁹ 1.71 × 10 ⁻⁹
BOT (MOT Hex Inv)	Ipp Isp	7.3×10^{10} 7.3×10^{10}	26.6 167.7	2.4	32.5 - 23.2 269 - 108	1.40	3.65 × 10 ⁻¹⁰
BOT (MOT Buffer)	Ipp qq ^I Isp	1.3 × 10 ¹⁰ 6.4 × 10 ¹⁰ 6.4 × 10 ¹⁰	13.9 67.0 493	2.0 12.2 114.5	19.4 - 10.6 99.0 - 43.0 708 - 203	1.83 2.30 3.49	1.07 × 10 ⁻² 1.05 × 10 ⁻⁹

*"Anomalous" Ipp due to secondary effects (such as transverse base resistance), decreased \sim X5 after repeated testing.

Table 53 Comparison of Electrical Storage Time and Storage Time Constant, as Screening Parameters for Primary Photocurrent

Device	Exposure		Rank Correlation Coefficient of I	oefficient of	dd.	
Type	[rad(Si)/s]	Electrical Sto	Storage Time, tSE	Electrical (Storage Time	Constant, ts
		$I_{CS} = 10mA$ $I_{B} = 2mA$	$I_{CS} = 50mA$ $I_{B} = 10mA$	Ics = 5mA	$I_{CS} = 10mA$	$I_{CS} = 50 \text{mA}$
969NC	1.2 × 10 ⁸	.391	.331	.426	797.	. 398
	5.3 x 10 ⁸	.514	.463	.531	.529	.504
2000NC	3.0×10^9	.283	.264	.274	.278	.309
	1.4 x 10 ¹⁰	.133	.123	.125	.130	.146
2N2905A	1.3 x 10 ⁹	154	.607	.243	.471	.604
	6.0×10^9	050	.594	.289	.470	. 586
096ENC	1.5 × 10 ¹⁰	.566	.570	. 559	.557	.482
	6.0 × 10 ¹⁰	.595	.610	. 534	.536	.358
			$I_{CS} = 20 \text{mA}$ $I_{B} = 4 \text{mA}$	$I_{CS} = 10 \text{mA}$	Ics	= 20mA
2N.709	8 × 10 ¹⁰					!
rok) ros	1.3 x 10 ¹⁰	\$67.	.377	.465	-	161
Buffer)	6.4×10^{10}	.478	.537	.371		.425

		Ranl	Correla	tion Co	effi ci en	t of I	vs:
Device Type	Dose Rate [rad(Si)/s]	C _{OB}	t _B	BV _{CBO}	h _{FEI}	r _{BI}	C _{IB}
2N696	1.25 x 10 ⁸	.013	099	.426	.176	.105	282
	5.3 x 10 ⁸	.079	123	.445	.248	.111	354
2N2222	3.0 x 10 ⁹	334	.320	.317	066	. 156	.413
	1.35×10^{10}	296	.184	.189	237	036	.501
2N2905A	1.3 x 10 ⁹	.498	246	. 249	. 501	.182	.013
	6.0×10^9	.538	312	.168	.511	.317	082
2N3960	1.5 x 10 ¹⁰	305	.566	.478	.000	585	.038
	6.0×10^{10}	232	.299	. 354	152	370	. 144
MT7113	1.3 x 10 ¹⁰	.180	.133	.295	.096	100	.284
	6.4×10^{10}	.133	075	.314	.180	.168	.076

Table 55

Relative Efficacies of Various Screening
Parameters for Primary Photocurrents

-51			Devic	е Туре			
Rank	2N969	2N2222	2N2905A	2N709	2N3960	MT7111	MT7113
(1)	τs	CIB	t SE	C _{OB}	t SE	C _{OB}	t _{SE}
(2)	t _{SE}	V CE(SAT)	τs	вусво	τs	C _{IB}	^t S
(3)	BV _{CBO}	СОВ	V _{CE} (SAT)		r _{BI}	t _{st}	BV _{CEO}
(4)	I EBO		СОВ			FEL	h _{FE}
(5)	V _{CE(SAT)}		h _{FE1}				
(6)	CIB						

Table 56 Summary of MLR Predictions of I $_{\mbox{\footnotesize{pp}}}$ for 2N696, 2N2905A and 2N2222 Low-Power Transistors Using Total Sample

Device	Dose Rate	No. Screening		Prediction	n Error	s (%)
Туре	[rad(Si)/s]	Parameters	Mean	RMS	Max	Min
211696	1.25 x 10 ⁸	3	1.2	11.5	33.3	-24.8
	5.3 x 10 ⁸	3	1.1	10.6	28.3	-25.9
	1.25 x 10 ⁸	12	1.2	10.4	36.8	-21.5
	5.3 × 10 ⁸	12	0.7	9.0	31.7	-17.2
2N2905A	1.3 x 10 ⁹	3	2.2	14.4	49.3	-34.1
	6 x 10 ⁹	3	2.9	18.3	45.6	-30.6
	1.3 x 10 ⁹	12	1.1	11.2	45.6	-19.8
	6 x 10 ⁹	12	_	14.4	37.2	-28.7
2N2222	3 x 10 ⁹	3	_	17.3	56.5	-26.8
	1.35×10^{10}	3		17.7	52.8	-22.2
	3 x 10 ⁹	12		15.8	53.5	-22.8
	1.35 x 10 ¹⁰	12		16.2	52.6	-23.6

Table 57 Summary of Rank Correlation Coefficients for \mathbf{I}_{sp}

	Exposure			Rank	Rank Correlation Coefficients of I	tion Coe	fficien	ts of I	sv vs.	
Device Type	hate [rad(Si)/s]	I Fp	r_{B}	hFE	NBO	t _B	$\mathbf{s}_{_{1}}$	tSE	VCE(SAT)	Other
2N2905 A	6.0 × 10 ⁹	777.	619.	.860	473	7744	.818	.845	.839	.865 (h _{FEI})
2N690	5.3 x 10 ⁸	. 858	. 334	.426	368	232	.736	.722	.739	.421 (h _{FEI})
2N2222	1.35×10^{10}	. 305	.765	.258	.053	.525	.782	.773	620	.649 (h _{FEI})
2N709	1						1	-	-	
2113950	6.0 × 10 ¹⁰	.305	.388	.281	.195	.274	.288	.212	.246	.239 (h _{FEI})
MT 7111		!	! !	}						}
MT 7113	6.4×10^{10}	.155	.101	.498	594	558	.425	.537	596	0.542 (h _{FEI})

Table 58 Summary of Rank Correlation Coefficients for Primary Photocurrent - Dual JFET

Electrical			rrgs	trigs	υţ	SSS	SSS
Parameter	(P)	(4) ^{d1}	$I_{\rm T} = 10$ mA $I_{\rm R} = 2$ mA	$I_{\rm F} = 10 \text{mA}$ $I_{\rm R} = 5 \text{mA}$		$(V_{GSS}=1V)$	$(V_{GSS}=20V)$
Rate [rad(SI)/s]	Chtp	gron					
7×10^{7}	Ą	ಶ	.951	2	സ	9	.239
, -	¥	m	.735	5	2	7	470
7 × 10 ⁷	∢	TOL	946.	776.	776.	. 732	.722
×	p;	ರ	.921	\sim	3	\sim	787.
×	В	G)	764.	6	9	59	510
	В	TOL	.910	-	3	72	. 766
;	4	 ਨ	ന	046.	.910	9	.223
. ×	< 4	(1)	.790	.818	.768	495	471
P:	Ą	TOT	4	.951	976.	\vdash	. 708
2 3	В	ਲ	\vdash	808.	676.	57	.441
.2 x	23	7)	CA	.828	.825	45	420
1.2 x 10 ⁸	В	TOT	\leftarrow	.882	.943	\sim	. 769
× 10	⋖	ਤ	.925	3	0	C	.239
8 108	A	œ	.785	.754	.781	534	577
70	Ą	TOT	.954	5	5	.721	.642
OT X	В	ರ	.862	1-	5	.183	.352
× 10	ex.	m	.762	9	t	383	387
и 10	æ	TOT	506.	1	C	.717	.750

The dual JFET has two chips, A and B, in the package. Group α = serial numbers 1-35 Group 2 = serial numbers 36-60(F)

,

Table 59

- Dual JFFT

Summary of MIR for I

(a)MLR coefficients were generated using 27 devices and the $I_{
m pp}$ of the other 23 were predicted usirg these.

(b)Independent variables were τ_S , N (calculated from capacitance data).

(c)Independent variables were $t_{\rm rr5S}$ ($I_{\rm F}$ = 5 mA, $I_{\rm R}$ = 10 mA) (J)Independent variables were $\tau_{\rm S}$, $I/C_{\rm SSS}$ (20V).

Table 60

Summary of TTL Transient Lonization Data

Device	Data Description (a)	Mean Value	Worst Value	Standard Deviation	Ratio [Max/Min]
TI Inverter	J-State Threshold O-State Threshold (100 mV)	1.13×10 ¹⁰ 5.6 ×10 ⁹	5.7x109	2.3x109 1.2x109	3.2
	0-State Threshold (200 mV)	9.2 .109	4.0x10 ⁹	2.9×109	4.7
TI	Modified Response - 1.2x1.09	0.20V	0.32V	0.0197	~2
Buffer	Modified Response - $3x10^9$	0.77V	1.32V	0.11V	~ 5
	Unmodified Response - $3x10^9$	0.34V	0.42V	0.038V	2.1
TI	300 mV Threshold	1.27x10 ⁹	0.54×109	2.6×10 ⁹	5
A-O-I Gate	600 mV Threshold	2.47×10 ⁹	1.5 ×10 ⁹	4.2×10 ⁸	2.7
Motorola	1-State Threshold (Pin 6)	1.03×10 ¹⁰	3.5×109	2.5×10 ⁹	09
Inverter	0-State Threshold (Pin 8)	3.45×10 ⁹	1.2×109	1.3x10 ⁹	5.3
	0-State Tireshold (Pin 6)	6.9 ×10 ⁹	1.2x10 ⁹	2.0×10 ⁹	6~
Motorola	0-State Threshold	8.8×10 ⁹	4.5×10 ⁹	901x6.1	2.3
Buffer	l-State Threshold	7.9×10 ⁸	8.7x10 ⁷	3.0x1.0 ⁸	~20

(a) "Modified" refers to the circuits which contain special leads.

 $\label{eq:table 61} \mbox{Some Rank Correlations for the $\dot{\gamma}$ Response of the TI Inverter}$

		tors for † Response us Parameters
Initial Electrical Parameter	0-State (Output Low)	l-State (Output High)
V _{OH}	-0.616 -0.715	-0.427 -0.493
I _{SK} V _{OS}	-0.647 -0.679	-0.520 0.738
Switching Time (Low to High) Active Rise Time	-0.438 -0.693	0.746 -0.630
ω _T	0.422	0.591
hFE Rise Time (Low to High)	-0.703 -0.591	-0.721 -3.771

 $\label{eq:table 62} \mbox{Some Rank Correlations for the $\mathring{\gamma}$ Response of the TI Buffer}$

	Correlation Factors for $\dot{\gamma}$ Response of Various Parameters			
Initial Electrical Parameter	1-State Response at 3 x 10 ⁹ rad(Si)/s (Side A)	1-State Response at 3 x 10 ⁹ rad(Si)/s (Side B)		
I _{SK}	0.436	0.462		
ISINK	0.709	0.521		
v _{os}	-0.705	-0.502		
h _{FE}	0.510	0.405		
Active Rise Time (Output voltage)	0.639	0.440		
Switching Time (Low to High)	0.130	0.464		
Switching Time (High to Low)	-0.414	-0.274		
I _{IN(1)}	0.522	0.504		
V _{BE} (Q5) [Note(a)]	0.550			

⁽a) Special Lead Measurement

Table 63

Some Rank Correlations for the Ionization Response

Threshold of the TI A-O-I Gate

Electrical Parameter	Rank Correlation with TI A-O-I Gate Ionization Response Threshold
Ios	284
^I cc(0)	.273
v _{os}	092
t _{PD}	323
Output Capacitance	289
Stored Charge	.170
h _{FE} (I _{SK})	.126
R ₆ (a) Resistance	248

(a) $\ensuremath{R_6}$ is the emitter-to-base resistor of the output transistor.

Table 64
MLR Results for TI A-O-I Gate Transient Response Threshold

Parameters Used For Regression	Prediction RMS	n Error ^(a) (%) Maximum
^I cc		
R ₆ (b) Resistance (Calculated)		
Propagation Delay Time	16	45
I Correlation Factor		
1/I _{OS}		

⁽a) The first 70 units were used for regression coefficients which were then used to predict the values of all 140 units.

⁽b) $R_{\hat{b}}$ is the emitter-to-base resistor of the output transistor.

Table 65

Some Rank Correlations for Ionizing Rate Response of the Motorola Inverter

	Correlation Factors for † Response of various parameters		
Initial Electrical Parameter	0-State (Output Low)	1-State (Output High)	
V _{OH}	-0.161	-0.342	
I _{IN} (1)	0.042	-0.131	
ISK	0.049	-0.160	
v _{os}	0.133	0.121	
Switching Time (Low to High)	0.084	-0.304	
$\mathbf{h}_{\overline{\mathbf{F}}\mathbf{E}}$	0.083	0.218	

 $\begin{tabular}{ll} Table 66 \\ Effects of Flectrical Screens on the Regression Results \\ for the Motorola Inverter & 1-State <math display="inline">\dot{\gamma} \ Threshold \\ \end{tabular}$

	Parameters Used For	F	Prediction Err	ror ^(a) (%)
Description	Regression	Value	RMS	Marimum
MLR Based on Circuit Measurements (Devices #41 & #47 included)	h _{FE} V _{OH} R ₄ (c)	13.2	136	891
MLR Based on Circuit Measurements (Devices #41 & #47 excluded)	h _{FE} V _{OH} R ₄ (c)	5.2	27	145

- (a) The first 70 units were used to generate the regression coefficients. The 1-state $\dot{\gamma}$ threshold was then predicted for (a) the 2nd 70 units when Devices #41 and #47 were included and (b) all 138 units when the two devices were excluded.
- (b) The two devices were excluded because of faulty pretest electrical characteristics:
 - (1) Device #47 hac excessive output leakage current (112 μA at V_{OH} = 5.5V)
 - (2) Device $\sqrt[4]{41}$ had an open base-emitter resistor (R₃)
- (c) R_4 is the external base-emitter resistor on the pull-up transistor.

 $\label{eq:Table 67} Table \ 67$ Some Rank Correlations for the $\dot{\gamma}$ Threshold of the Motorola Buffer

	Correlation Factor for y Response of Various Parameters			
Initial Electrical Parameter	0- State Re • onse (Output Low)	l- State Response (Output High)		
I _{SK}	-0.695	0.040		
v _{os}	0.217	0.234		
V _{OH}	0.331	-0.173		
h _{FE}	-0.708	-0.052		
Switching Time (Low to High)	-0.532	0.131		
Switching Time (High to Low)	0.178	-0.027		
Stored Charge (Peak Current)	0.546	0.096		
R ₃ (a)	-0.267	-0.081		
Depletion Width plus Diffusion Length	0.381	0.193		

⁽a) R_3 is the emitter-to-base resistor on the output transistor

 $\label{eq:table 68} \mbox{Regression Results for the Motorola Buffer $\mathring{\gamma}$ Threshold}$

Description	Parameters Used For Regression	F Value	Prediction Err	cor ^(a) (%) Maximun
MLR Based on Circuit Measure- ments for 0-State Threshold	. h _{FE} . Stored Charge . Rise Time (low to high) . Switching time (Low to High) . R ₃ (c)	27	15.7	36
MLR Based on Circuit Measurements for 1 state Threshold (Device #40 included)	. h _{FE} . V _{OL} . V _{OS} . Switching Time (High to Low) . Fall Time (High to Low) . R ₄	2.1	9 9	964
'LR Based on Circuit Measure- ments for 1-State Threshold (Device #40) excluded)	. h _{FF} . V _{OL} . V _{OS} . Switching Time (High to Low) . Fall Time (High to Low)	2.1	56	163

(a) The first 70 units were used to generate the regression coefficients, and then predictions were made on all 140 units.

(b) Device #40 was excluded to observe the effect on the regimession coefficients because the measured $\dot{\gamma}$ Threshold for Device #40 was a factor of four (4) lower than the other devices.

(c) $\rm R_3$ and $\rm R_4$ are the external base-emitter resistors for the output and pull-up transistors, respectively.

Table 69
Summary of Ionizing Rate Data (Non-TTL Integrated Circuits)

Device	Data Description	Mean	Worst Value	Standard Deviation	Max /Min
m.r	I _{pp} @ 3.5x10 ^{8*}	3.59 mA	4.1 mA	0.19 mA	1.33
TI Word	I _{pp} @ 3.3x10 ^{9*}	25.1 mA	30.4 mA	2.2 mA	1.5
Switch	I Threshold	8.9x10 ⁸ *	7.7x10 ^{8*}	7.2x10 ⁷ *	1.4
Fairchild	Response @ 4.3x10 ⁶ *	0.59V	1.1V	1.5V	9.5
μ Α744	Sat. Threshold	1.62×10 ^{7*}	7.0x10 ⁶	4.8x10 ^{6*}	8
Op Amp	Sat. Time @ 9x10 ⁸ *	15.6 µs	41 µs	5.8 µs	45
МОТ	Threshold	2.26×10 ^{8*}	2.7x10 ^{7*}	7.9×10 ^{7*}	12
Sense Amp	CH 2 Threshold	1.36×10 ^{8*}	1.5x10 ^{7*}	5.1x10 ^{7*}	18

^{*} Dose rates in [rad(Si)/s]

Table 70
Some Rank Correlation Factors for the Ionization Response of the Word Switch

Electrical	Rank Correlation Coefficient			
Parameter	I @ 3.3 x 10 rad(Si)/s	I Threshold		
Storage Time	.308	701		
90 Ω Resistor ^(a)	166	 725		
h _{FE}	240	692		
V _{BE}	167	496		
Capacitance	251	.097		
I Correlation pp Factor	039	695		
t _{OFF}	.499	.484		

⁽a) Base-emitter resistor of the output transistor

Parameter Used For Regression	Prediction Error (a) (%)		F Value
	RMS	Maximum	value
Storage Time 90 \(\Omega\) Resistor Value (b) h FE Output Capacitance	3.91	21.5	71.1

- (a) The first 70 units were used to generate the regression coefficients, and the coefficients were then used to predict all 140 units.
- (b) Base-emitter resistor of the output transistor.

Table 72

Some Rank Correlation Coefficients for the Ionizing Rate Response of the Motorola Sense Amp

	Rank Correlation Coefficient				
Initial Electrical Parameter	Response Threshold Channel 1	Response Threshold Channel 2			
Power Supply Current	.055	.127			
V _{OL}	.057	.141			
V _{OH}	.132	125			
v _{os}	141	177			
^I os	001	037			
¹ BIAS	080	.100			
^A OL	.129	209			
Recovery Time	053	087			
Channel Select Time	108	238			
Output Resistance	207	149			

Table 73

An Example of MLR Predictions for the Ionizing Rate Response of the Motorola Sense Amp

Electrical Parameter	Prediction Error ^(a) (%)		F Value
	RMS	Maximum	
Power Supply Circuit			
Output Current (1V)			
v _{он}	109	676	2.2
v _{os}			
A _{OL}			
Recovery Time			

(a) First 70 units used to generate MLR coefficients. All 140 units used for prediction.

Table 74

Some Rank Correlation Coefficients for the Ionization Response of the uA744 Op Amp

Initial	Rank Correlation Coefficients for Transient Lonization Data	ansient Ionization Data
Electrical Parameter	Response at $4.3 \times 10^6 \mathrm{rad}(51)/\mathrm{s}$	Saturation Threshold
Saturation Recovery Time	.515	857
Slew Rate	. 506	728
Icc	.625	721
$^{ m A}{ m OL}$.127	178
Input Capacitance	.205	502
BIAS	.255	533
so	165	.292

Table 75 $$\rm MLR$ Results for the Ionization Response of the $\mu A744$ Op Amp

and the second s				
Initial Electrical Parameters Used For Regression	RMS Prediction Error For Output Response At 4.3x10 ⁶ rad(Si)/s	F Value For Regression	RMS Prediction Error For Saturation Threshold	F Value For Regression
Saturation Time. Slew Rate Power Supply Current Input Capacitance	201%	18.1	%07	23.6

Table 76
Failure Rates for Parts Subject to Ionizing Rate Tests

Device	Catastrophic Failure Rates (a) (Percent/1,000 hours at 60° Confidence)	
Group Type	Control	Stressed
Hex Inverter	1.1	.63
Dual Buffer	3.2	1.4

(a) Drift failures were not included in the failure rate calculations, (1) for the reasons stated in Paragraph 1d, Section V, Volume I and (2) because the particular circuits would still have functioned properly in normal practical applications.

SECTION IV

IONIZING RADIATION TOTAL DOSE HARDNESS ASSURANCE

1. INTRODUCTION

This section discusses the results of the work carried out on the total dose aspects of hardness assurance.

The primary objectives of the study were first, to identify certain surface related electrical parameters which could be used as precursors of radiation sensitivity and hence, which could enable one to predict the expected total dose damage. The second objective was to assess the feasibility of the low dose screening technique. Specifically, the objective was to test the assumption that the devices exhibiting the highest radiation sensitivities during a low dose exposure are the ones most likely to fail at higher doses.

Paragraphs 2 and 3 present the electrical and low dose screening results, respectively, for a group of low-power transistor. Similarly Paragraphs 4 and 5 perform the same functions for an operational amplifier.

2. ELECTRICAL SCREENING - LOW-POWER TRANSISTORS

a. Approach

The following material presents the results of the effort expended in evaluating electrical measurement techniques suitable for screening low-power transistors for total dose effects. The devices selected as vehicles for the study were: 2N709 (npn), 2N930 (npn) and 2N2905A (pnp).

The technical approach to the problem of evaluating electrical screening parameters was to determine the rank correlation coefficients between certain promising surface related, initial parameters and radiation sensitivity. The use of the rank correlation technique immediately implies that the scope of the program was primarily geared to the prediction of the relative radiation sensitivities between devices of different types and of a given type.

The rationale behind the selection of the correlation parameters for the bipolar transistors was discussed in Paragraph 4-a, Section V, Volume 1 and will not be repeated here. The summary of the results of the rank correlation calculations are shown in Table 77 in a sort of generalized form which gives an overview of the total dose task. (The specific list which would also indicate the exact bias conditions is prohibitively long.) As discussed in Paragraph 4, Section V, Volume 1 and as is evident in the tables, correlation was sought in the majority of cases between certain surface dependent initial parameters (or combinations of these) and the "radiation sensitivity" of the device. The radiation sensitivity was thought to be adequately represented by the absolute or relative radiation induced change in the base current. For increased measurement sensitivity the base current was measured at low injection levels (with both fixed \boldsymbol{V}_{BE} and fixed \boldsymbol{I}_{E} conditions) where the surface effects are dominant. Of course, there are other quantities of practical importance in Table 77, besides the radiation sensitivities, for which correlations with initial parameters were sought, e.g., the absolute and relative changes in gain.

Total dose effects are extremely variable both between device types and between derices of a given type. The three types of low-power transistors, 2N930, 2N709 and 2N2905A, had high, moderate and low radiation sensitivities, respectively. This is shown in Figure 77 where the mean value of the relative change in gain is plotted as a function of dose. (The lower end of the operating current range was used in these plots for increased sensitivity.) The histograms of Figures 78 through 89 illustrate the variability in radiation sensitivity of presumably identical devices. The radiation sensitivities are represented here by low injection ΔI_B , I_B/I_B^0 , $\Delta (1/h_{FE})$ (= $\frac{\Delta I_B}{I_C}$), and h_{FE}/h_{FEO} . Tables 78 through 80 show the mean and the covariance of these quantities at various injection levels to give a better overall picture. (Note that the following bias conditions were applied during gamma exposures. 2N709: V_{CB} = +10V and I_E = 20 ν A, 2N930: V_{CB} = +26V and I_E = 50 ν A, 2N2905A: V_{CB} = -30V and I_E = 40 ν A.)

b. Discussions and Conclusions

By scrutinizing the rank correlation tables the following conclusions can be drawn:

- 1. One of the promising initial parameters, the low frequency 1/f noise showed little correlation with radiation sensitivity. A possible explanation may be that the 1/f noise contains a current dependent term which prevents the determination of the density of the slow states in ungated devices. Hence, any ranking of the devices on the basis of noise will not necessarily mean a corresponding ranking in the density of the slow states. This latter quantity was the one with which correlation with radiation sensitivity was anticipated. Apparently, the current dependence of the 1/f noise obscured any significant correlation.
- 2. Surprisingly the radiation induced ΔI_B (low injection) did not always correlate well with ΔI_B (high injection) especially at the high end of the operating current range for the 2N709 and the 2N2905A. The correlation is quite good for 2N930. Consequently the practice of using ΔI_B (low injection) for predicting radiation sensitivity at high injection levels, just because ΔI_B (low injection) offers a great increase in measurement sensitivity, has to be treated with caution. The explanation of this effect is not clear at the present time.
- 3. No significant correlation was found between the radiation sensitivity and various initial parameters, e.g., burn-in changes, I_B, I_{EBO} (or BV_{EBO}) measured at various temperatures, etc. In fact, the correlation is practically non-existent for the 2N930, slight for the 2N709, and moderate for the 2N2905A. Even the moderate values (≈0.7 0.8) of the rank correlation coefficients for the 2N2905A are far too low to expect any of the various initial purameters to be meaningful screening parameters.

The lack of a strong correlation discussed above is perhaps not too surprising. For example: It is well established that the magnitude of the surface components of the preand post-irradiation I_{R} is controlled by two primary factors, namely, by the amount of charge within the oxide and by the density of interface states in the mid gap region. Either of these factors can be lominant in certain cases. Also, it has been shown in the past that in certain oxides there was a correlation between the pre- and post-irradiation density of the interface states (Ref. 18). In such cases, one may expect a correlation between the initial I_{R} and the radiation induced change in $\boldsymbol{I}_{\boldsymbol{B}}$ as long as the surface component is always dominated by the interface states; this confid have been the case for the 2N2905A. It should be noted that the radiation induced excess base currents (good indicators of radiation sensitivity) tended to be higher in those 2N2905A devices which had higher base currents initially.

In constrast, the amount of radiation induced charge accumulation has not been found to correlate with the initial amount of oxide charge (or the initial interface state density). Hence, whenever the oxide charge dominates the surface component of either or both of the pre- and post-irradiation $I_B s$, one does not expect to find any correlation between the initial I_B and the radiation induced changes in I_B . Such might have been the case for the 2N709 and even more so in the 2N930 since the rank correlation coefficients were very 1 c w.

4. The consistently high correlation between h_{FEO} and Δh_{FE} is not significant since contrary to expectations it does not guarantee high correlation between pre- and post-irradiation gains, h_{FEO} and h_{FE} , respectively.

The high rank correlation between $h_{\rm FEO}$ and /h , simply implies that devices with higher initial gain will suffer in general more gain loss. This is quite obvious e.g., whenever

the radiation induced base current increase, ΔI_B , is approximately the same for all devices of a given type. Although ΔI_B does vary among the devices (see histograms of ΔI_B in Figures 78, 82, 86) apparently the spread is not large enough to obscure the correlation between h_{FEO} and Δh_{FE} .

The utility of the high correlation between h_{FEO} and h_{FE} seems to be limited and the results should be viewed with caution. The correlation appears to offer a useful screening technique against h_{FE} failure [defined by $h_{FE} < (h_{FE})_{min}$] since the initial h_{FEO} distribution can be simply truncated. Figures 90 through 92 containing 2N2905A, 2N709and 2N930 data show the futility of this approach since all of the low gain devices do not fail first. (Incidentally, observe that that the h_{FEO} versus Δh_{FE} correlation is high in all cases; clearly a useless result especially for the 2N930 devices.)

It should be noted that the relatively high rank correlation values for the 2N2905A and in one case for the 2N709 are partially due to the fact that the gain degradations at the higher currents were relatively small. The rank correlation is expected to go down with higher relative gain loss. Furthermore, and this may be the root of the problem, since the degree of correlation between pre- and post-irradiation gain is very much oxide dependent, one cannot be sure ahead of time that a high $h_{\mbox{FEO}}$ versus $h_{\mbox{FE}}$ correlation will exist for any given untested device type. This can be checked out only by extensive experimental work which is just what we are trying to avoid by a simple electrical screen.

In other words, any given <u>initial</u> parameter which shows a good correlation with radiation sensitivity only in certain transistor types but not in others and whose behavior is not predictable, will have only limited significance, if any. Right now such seems to be the case with those initial parameters yielding reasonable good correlation in the 2N2905A but not in the 2N709 or the 2N930.

6. Higher gain devices tend to suffer more relative gain loss $(\Delta h_{FE}/h_{FE})$ in certain device types. The effect is clearly indicated for the 2N2905A, slightly indicated for the 2N709 and is completely absent for the 2N930. Again, the problem of complete inconsistency in behavior among the device types makes it impossible to generalize.

3. LOW-POWER TRANSISTORS - LOW DOSE SCREENING

The basic idea behind low dose screening is that devices which exhibit a relatively large radiation sensitivity during a low dose exposure are the ones which are most likely to fail after exposure to a larger dose. The approach to test this hypothesis was rather direct; comparisons were made of the tails of the histograms of radiation sensitivities at low and at high doses. The radiation sensitivities were defined in terms of $I_{\rm R}$ changes at both low and high injection levels. First, an arbitrary value of Δl_{R}^{*} at high dose was selected and it was asserted that all devices with values of $\Delta I_{B} \geq \Delta I_{B}^{*}$ were to be rejected by the screen. The position of each $\Delta \mathbf{I}_{\mathbf{R}}$ of the devices in this group was then located on the low dose historgrams. Were they also located at the appropriate tail? In general they were not and hence, the reliability of low dose screening is very much in doubt. This conclusion was also supported by the rank correlation coefficients between the quantities ΔI_R (low dose) and ΔI_R (high dose). As shown in Table 81 the values of the correlation coefficients are much lower than might have been expected.

In the following material, the results and conclusions for each device type will be discussed separately.

a. 2N930

Histograms of ΔI_B @(3.0 x 10⁵ rads) and ΔI_B @(1.0 x 10⁵ rads) were compared at four test conditions. Devices in the part of the histogram with the largest ΔI_B @(3.0 x 10⁵ rads) were generally scattered through a relatively large part of the histogram showing the ΔI_B s at 1.0 x 10⁵ rads (see Figure 93). These data are summarized in Table 82 where it is shown, specifically, that to eliminate the N devices having largest ΔI_B in the R rows of the 3.0 x 10⁵ rads histogram would require

screening out M devices contained in the P rows of the 1.0 x 10^5 rads histogram. Both Table 82 and Figure 93 emphasize the fact that low dose screening does not seem to be a viable technique for our 2N930 transistors.

b. 2N2905A

The data for the 2N2905A can be treated in the same fashion as that for the preceding device type, 2N930.

To eliminate the N devices having largest ΔI_B in the R rows of the 5.6 x 10^6 rads histogram would require screening out M devices contained in the P rows of the 1.7 x 10^5 rads histogram (see Figure 94 and Table 83). On the basis of these data, the low dose screening does not seem to be a viable technique for our 2N2905A transistors.

c. 2N709

Histograms of ΔI_{R} (1.7 x 10^{5} rads) were compared with histograms of ΔI_R (1.3 x 10^6 rads) at three bias conditions, I_E = 100 μA , 10 μA , and 3 μA . In the $I_{\rm E}$ = 100 μA and 10 mA data devices in the part of the 1.3 x 10^6 rads histogram with the largest ΔI_R were found in the higher tail of the lower dose $(1.7 \times 10^5 \text{ rads})$ histogram. The best predictability seems to occur for the 100 μA bias condition. The results at $I_{_{\rm T}}$ = 3 μA showed significantly poorer predictability and were more like the data analyzed for the 2N930 and the 2N2905A. One apparent difference in the histograms of ΔI_{R} for the 2N709 is that the maximum values of ΔI_{R} were 1.5 to 4 times the mean, whereas for the 2N930 and 2N2905A device types the large values of ΔI_p were typically only 20% to 50% greater than the mean. In other words, the coefficient of variation for the 2N709 distribution was much larger for the 2N709 than for the other device types. Table 84 summarizes the capability to eliminate the N devices in the Rrows of largest ΔI_R in the 1.3 x 10^6 rads histogram by screening out P rows containing M devices in the 1.7×10^5 rads histogram. Figure 95 shows an example of the procedure used in the analysis. As seen in this figure and in Table 84, the low dose screening does not seem to be a viable technique for our 2N709 transistors.

4. ELECTRICAL SCREENING - µA744 OPERATIONAL AMPLIFIER

The problems of predicting total dose damage for the $\mu A744$ operational amplifiers are in many ways similar to those encountered with the bipolar transistors. The most sensitive parameters of an op amp in a total dose environment are the input bias currents which are simply the base currents of the input transistors. It is important to note, however, that the radiation induced increase in I_B is somewhat reduced, one might say partially compensated, by the constant emitter current biasing circuit.

The rationale behind the selection of the primary correlation parameters, the bias currents, was discussed in Paragraph 4-b, Section V, Volume 1 in some detail and will not be repeated again. The radiation sensitivity is defined by the absolute or relative changes in the bias currents, similar to the procedure used for bipolar transistors.

The $\mu A744$ op amp exhibited a "medium" radiation sensitivity in I_B during total dose exposure. Although not very high it was by no means negligible! (It should be noted that the op amps were irradiated at bias voltages of +15V and -5V respectively in order to maximize the reverse biases across the junctions during exposure.) The initial base current, I_B^o distribution is illustrated in Figure 96, and the effects of the radiation are shown in the ΔI_B and the I_B histograms in Figures 97 and 98. The data emphasizes one very important message. The use of a failure level definition of $I_B \geq 750~\mu A$ essentially a Honeywell specification will reject 6%, 17% and 21% of the op amps after doses of 2.7 x $10^5~\rm rads$, $1.3~\rm x~10^6~rads$ and $5.6~\rm x~10^6~rads$, respectively.

Table 85 shows the rank correlation coefficients between the various initial parameters (noise and others related to I_B) and the radiation sensitivities of the op amps. As seen, there is a definite hint of correlation between the relative changes in the bias currents and the initial parameters. However, the values of the coefficients (≤ 0.5) are not high enough to have any statistical significance for screening purposes.

5. LOW DOSE SCREENING - uA744 OPERATIONAL AMPLIFIER

The approach to test the applicability to the µA744 of the basic premise of the low dose screening, "devices exhibiting high radiation sensitivity at low dose are the ones most likely to fail at high dose" was the same as presented for bipolar transistors. Namely, the tails of the histograms of the "radiation sensitivity" (measured by the change in the bias current, I_B) at low and high doses were compared to determine if the devices maintained their relative positions in the two histograms. As for the bipolars, the simple approach to low dose screening did not work. Too many devices would have had to be eliminated after the low dose test in order to make sure that those few exhibiting excessively high radiation sensitivity at the high doses were indeed removed. This conclusion is further supported by the following poor rank correlation value between low and high dose radiation sensitivities.

Low Dose Sensitivity	High Dose Sensitivity	Correlation Coefficient
$[I_{B}(2.7 \times 10^{5} \text{ rads}) - I_{B}^{0}]$	$[I_{B}(5.6 \times 10^{6} \text{ rads}) - I_{B}^{\circ}]$	0.629

After eliminating from consideration all devices with poor or suspect data we found that those devices in the 5 rows of the histogram corresponding to the largest values of ΔI_B at 5.6 x 10^6 rads were scattered almost randomly through 15 rows of the highest ΔI_B s in the 2.7 x 10^5 rads histogram. Precisely, to screen out the N devices in the highest R rows of the 5.6 x 10^6 rads histogram requires elimination of the highest P rows containing M devices in the 2.7 x 10^5 rads histogram. The results are summarized in Table 86. Again, the conclusion is the same as for the bipolar transistors i.e., the low dose screening did not seem to be a viable technique for our μ A744 op amps.

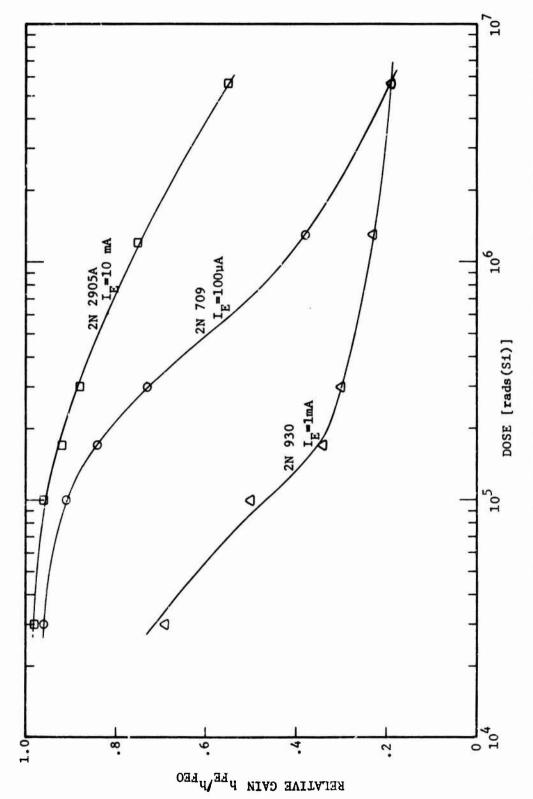


Figure 77. Illustration of the Relative Radiation Sensitivities of 2N709, 2N930 and 2N2905A

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Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10^6 rads; I_E = 3 μA) Figure 78.

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Figure 79.

Histograms of I_B/I_B^0 Illustrating the Variatior in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10^6 rads; $I_E=3~\mu A$)

######################################								
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2.0.65_0.3 4.69_0.2 4.69_0.2 1.00_0.1 1.00		20-179	•					
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4.456-02 4.456-03 4.456-		1045-02	•	:	1	•		
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2.35E-01	-	1C-30r	.443527567					
2.375-31 .444452459595959594695 2.325-31 .444452469746951528953952 2.325-31 .45544597469521528953564 3.315-31 .45544597469525561 3.315-31 .455455951856361 3.315-31 .455459518561 3.315-31 .455459518561 3.315-31 .455459518561 3.315-31 .455459718561 3.315-31 .455459718576 4.315-31 .4574648749496593851854 4.315-31 .4574648749496593851854 4.315-31 .4574648749496593851854 5.315-31 .4574648749496593851854 5.315-31 .457464874949659386 6.315-31 .537572 6.315-31 .537572 6.325-31 .537572 6.355-31 .53757	~	1.4E-01	. 4464 4046 1549					
2.52E-01 .445445744952152853554 2.5E-01 .457474495525564 3.5E-01 .45744465774495525564 3.5E-01 .45744401952333355669 3.5E-01 .45744401952333355669 3.5E-01 .4474649371576 4.01E-01 .44746493715731543 4.71E-01 .44746493715731543 4.71E-01 .447464937047150751543 4.71E-01 .44746493715731543 4.71E-01 .44746493715731543 4.71E-01 .447464937173 5.45E-01 .4475537 5.45E-01 .44752536 5.45E-01 .47657173 5.45E-01 .47657173 5.45E-01 .47657173 5.45E-01 .47657173 5.45E-01 .47657173 5.45E-01 .47657173 5.45E-01 .47657173 6.45E-01 .476773 6.45E-01 .47657173 6.45E-01 .47657173 6.45E-01 .47657173	i	375-01	. 4444 5245 851 9520545951 95859	y5e9				
2.95E-31 .44044574794355254655564 3.15E-31 .4534457455561 3.15E-31 .453445764555561 3.55E-31 .4534457641527531543 4.01E-31 .453446476471527531543 4.45E-31 .453446494657315763 4.45E-31 .453446494657315767510577 4.45E-31 .453446494657575757 5.15E-31 .45344575 5.15E-31 .443475757 5.15E-31 .501515757 5.15E-31 .501515757 5.15E-31 .501515757 5.15E-31 .501515757 5.15E-31 .50151577 5.15E-31 .50151577 6.15E-31 .50151577 6.15E-31 .50151577 7.75E-01 .5015177 7.75E-01 .5015177 7.75E		10-30-	.44545445344049952152853253	3562				
3.51 - 01		10 - 375	4474474474747043497525446F	1557564				
3.31E-01 .451C554561 3.51E-01 .45254561155214545464634 4.01E-01 .44754514534543 4.01E-01 .4354641757531543 4.01E-01 .43546417547531543 4.71E-01 .4354641744474545505747 4.71E-01 .435464174447454505747 5.45E-01 .4345017 5.65E-01 .50151575 6.11E-01 .50151575 6.12E-01 .50151575 6.12E-01 .537572 6.12E-01 .537572 6.12E-01 .537572 6.12E-01 .54574 7.25E-01 .54574 7.25E-01 .54574 7.25E-01 .54574	, -	175-11	45 14 14 14 14 14 14 14 14 14 14 14 14 14				1	
3.75-01 4-21-21-25-25-25-26-9 3.77-01 4-21-21-25-23-25-26-9 3.77-01 4-21-21-25-23-25-26-9 4.010-01 4-31-40-41-25-23-25-26-9 4.010-01 4-31-40-41-40-41-20-21-25-24-24-24-21-25-24-24-24-24-24-24-24-24-24-24-24-24-24-			000000000000000000000000000000000000000					
3.55-01 -4474.01912121494644511576 4.01E-01 -447414912151244544511576 4.01E-01 -4474149121512518543 4.24E-01 -44741491491219518543 4.34E-01 -44741491491819519519 4.34E-01 -434444657439919519573 5.45E-01 -434444654739919519573 5.45E-01 -43443017 5.45E-01 -43443		101111	196666316969669164*	7				
4.0E-01 .4434611012515453464511576 4.0E-01 .4434616234510543 4.24E-01 .4434616239595159363 4.24E-01 .443464659359751505731543 4.24E-01 .443464659359751505731543 4.34E-01 .4437641147494405547 4.34E-01 .4344917474446541569 5.13E-01 .434491749446541569 5.13E-01 .434491749446541569 5.13E-01 .502536538 6.1E-01 .502536538 6.1E-01 .502536538 6.1E-01 .516574 7.25E-01 .516574 7.25E-01 .516574 7.35E-01 .516574		10-5-5	.44748.4~14425135235353555656	•				
4.01E-01 .444-614-3470-71531543 4.24E-01 .443-64525659526542 4.24E-01 .433-645693507510570 4.71E-01 .45546.6973507510570 4.71E-01 .45546.6973507510570 5.41E-01 .454-757375 5.65E-22 .501515775 5.65E-21 .502536534 6.11E-31 .602536534 6.35E-01 .516574 7.25E-01 .72E-01 .72E	1	10-311	.450511512514534544571570					
4.24-01 .4344624724834956542 4.48-01 .43444340693505510370 4.34-01 .43444440693547 4.34-01 .434442537 5.13-01 .43443237 5.65-01 .50151537 5.86-01 .502536538 6.15-01 .516574 6.35-01 .53757 6.35-01 .516574 7.25-01 .516574 7.25-01 .516574 8.22-01 .516574		10-310	.445-614-3470471507531543					
4.48f-01 +554r(4)f4251309510570 4.74f-01 +077bet1744205547 4.74f-01 +077bet2744420547 4.74f-01 +077bet27474420541569 5.14f-01 +194:25539 5.41f-01 +194:25539 6.11f-03		.245-01	.4334624724834955Ct 50952654	~				
4.71E-01 407768417454005547 4.44E-01 494342444554390541548 5.41E-01 49432317 5.41E-01 49432317 5.41E-01 502336538 6.11E-01 502336538 6.11E-01 5.45572 6.35E-01 5.45574 7.25E-01 7.25E-01		.6-384	.45546667548549650350851057				: : : :	:
4, 14E-01, 4344ftuc 5473500541569 5,13E-01, 149452537 5,65E-01, 50151575 5,65E-01, 502536538 6,13E-01, 502536538 6,13E-01, 537572 6,35E-01, 537572 7,05E-01, 516574 7,27E-01, 7,52E-01 7,52E-01, 7,52E-01 7,52E-01, 7,52E-01		10-311	- 40746E47448447494505547					
5.13E-01		345-01	43 14 + 64 54 735 3054 1558					
5.41E-01	i	136-01	- ASH3 35530					
5.65E-01 501514575 6.11E-01 502536534 6.15E-01 537572 6.35E-01 516574 7.05E-01 516574 7.25E-01 7.52-01 7.52E-01 7.52-01 7.52E-01 7.52-01		10-9:4	11000000					
5.89E-01 50253e538 6.11E-01 6.32E-01 537572 6.34E-01 7.05E-01 7.05E-01 7.52E-01 7.52E-01 7.52E-01 7.54E-01 7.55E-01 7.55		16-35	501515573					
6.11E-31 6.15E-01 6.15E-01 7.05E-01 7.52E-01 7.52E-01 7.55E-01 7.55E-01 7.55E-01 7.55E-01 7.55E-01 7.55E-01 7.55E-01 7.55E-01 7.55E-01		.8 AF-3!	. 50233653B					1
6.35E-01 .537572 6.75E-01 .516574 7.25E-01 .516574 7.55E-01 .75E-01 .7		1116-31						
6.54E-01 6.3E-01 7.2E-01 7.2E-01 7.5E-01 7.7E-01 7.7E-01 8.22E-01		19-5-11	.537572					
6.32E-01 7.05E-01 7.52E-01 7.55E-01 7.55E-01 8.22E-01	1	10-18-						i
7.35E-01 .516574 7.25E-01 . 7.75E-01 . 7.75E-01 . 8.22E-01 .		3.25-7.1						
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7.555-01 7.755-01 7.755-01 8.225-01	•	101100	* 1 6 3 7 6 .					
7.75E-01 . 7.79E-01 . 8.22E-01 .		10-22						
7.775-01 • 7.44E-01 • 8.22E-01 •		10-374	•					
8.22E-01 .		155-01	•					
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200		.22E-01	•					
15 20		******						4
07			0	10	15	20		

Histogram of h_{FE}/h_{FEO} Illustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10⁶ rads; I_E = 100 $\mu A)$ Figure 80.

A

5	PE 4 CF 4T	7657		KEDIAN 4.436E-02	ME AN 5-2145-02	3.074E-02	CI:VAR. (\$) 58.96	
c	0	-4.75E-02						
\$	6.0	-4.17:-32-	•					
0	0.0	-3.50E-02	•					
c	0	-3.035-02	•					
۲,	0.0	-2.465-32						
٠,	3.3	-1.44E-02	•					
2	0.0	-1.315-02	•					
~	0.0	- 3 - 3 - F-D3						
~	0.0	-1.556-33	•					
•	0.0	4.072-07	•					
÷	C	6.7 = -34		- 20 N - was				
٠,	~;	1.008-02	. 502537568					
1	2.0	20-1-1-2	.493490501515516517525526538541	8541				
4	,	2.76 - 62	. 441462463484500506565675095425475 04570571574574	2547504570573	£.			
•	10.2	3.275-32	.44948444503504510526543544554557572575	4554557572575				
.4		3.5-5-52	. 4944664d3487495+96511534F39549546	354456				
~		6 - 5 - 7 - 2		2473474475482	491492505531	5355515595615	. 96	
		.0.	.+344-241451453472512554518323355569	£92355555				
-	9,		. 4-7-4-50-5-4-5-7-4-7-1-4-34-5-4-46-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-4-6-5-5-5-4-6-5-5-6-5-5-5-6-5-5-5-6-5-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-6-5-5-6-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-6-5-5-6-5-5-6-5-6-5-5-6-5-5-6-5-6-5-6-5-5-6-5-5-6-5-5-6-5-6-5-6-5-6-5-6-5-6-5-6-5-6-5-6-5-6-5-6-5-6-6-5-5-6-5-5-6-5-6-5-6-5-6-5-6-5-6-5-5-6-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5-5-6-5	4554				
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e	67	6.715-02	.4.5544576					
-	2 - 3	7.295-02						
¥	o• -	7.45-02	goefan.			0 0 0		
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r	5.0	9.1.5	**************					
?	0.0	4.57E+32						
~	0.1	1.025-01	. 430485					
C	Ċ	10-000						
÷	0	1-136-01						
7	9.	10-101-01	. 437452					
-4	0.3	102-	.5.7					
0	-0.6-	10-30 2-1						
4	0.00	1.365-21	. 552					
7	1.6	1.415-11	025165					
C	0.0	10-37 4.						
^	2.0	1.535-01	. 527550					
	0.0	1.538-31						
7	0.0	10-246-1						
~	ç,	1051-1	.545					
125		1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	.0	Īo	1.5	0.7	25	! ! ! !
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Histogram of $\Delta(1/h_{\rm FE})=\Delta I_{\rm B}/I_{\rm C}$ Illustrating the Variation in the Radiation Sensitivities Among the 2N709 Transistors of Different Wafers (Dose = 1.25 x 10⁶ rads; $I_{\rm E}=100~\mu{\rm A})$ Figure 81.

COCCC444 4.4134-31 N. 0.10533 1.7675-01

CENT TEST	PER TEST	10aVCB 0 V 3029033040 20140170120202702803V 032C 5014017012020202702803V 032C 50140170120202702803V 032C 50140170120202702803V 032C 5014017012020202702803V 032C 501401701202020202702803V 032C 50140170202020202020202020202020202020202020	. 672 C-07	#FA4 1.532E-07 55101121154	\$10. DEV.	COVAR.(E)	
2.000	2.4 4 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6	302933040 2014017014022027028030C32C 5014024025034028059041062C 1014020021026031034035037 1014112	50 50 50 50 50 50 50 50 50 50 50 50 50	\$\$107171134			
11.5	11.5 1.0 2 4 2 4 2 6 6 6 6 6 6 6 6 6 6 6 6 6 6 6	302933040 2014011014022027028030C32C 5014024025036C36C3605061062C 1016C20021026031C34035037 1018112 1018115	50 5075433 39041C420540	\$\$107121134			
11.00 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	11.5	3029033040 2014017014022027028030232 5014024025036036054061662 4081427102119 7083142	50 5075133 590410420540	\$\$107171134			
11.5	2.000 - 2.000 - 0.000	3029033040 2014017018022027028030232 50140240250360360340054061662 5014024025036028033634035037 3043142 3043142	50 50 50 50 50 50 50 50 50 50 50 50 50	55101121154			
11.5	2.00 2.00 8.00 8.00 8.00 8.00 8.00 8.00	3029033040 2014017016022027028030032 5014024025034034054061662 5014024025034034034035037 3014145	60 65075133 390410420540	\$\$101121154			
11.5	2.056.03 0.00 - 2.066.03 0.00 - 3.206.03 0.00 - 5.206.03 0.00 - 5.206.03 11.5 - 6.206.03 11.5 - 6.206.03 11.5 - 6.206.03 11.5 - 6.206.03 11.5 - 6.206.03 12.6 - 6.206.03 12.6 - 6.206.03 13.6 - 6.206.	392933040 2014017014022027028030C32C 5014024025036036059061062C 1016020021026031034035037 10831627102119	5075133	\$\$101121154			
11. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2.	2.00	3029033040 2014017018022027028030232 5014024025036038059061662 4081047102119 7083142	50 5055133 390410420540	55101121154			
10.00	20.00 - 3.8 (19-08 - 10-08 - 1	3029033040 2014017018022027028030332 5014024025036036034061662 501402402503603634034034081 3083142 3144155	50 5975133 39041C42054C	\$\$101121154			
2.0 0 4.78 - 0.0 0 6.78 - 0.0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	0.00 4.778 - 08 6.00 6.00 6.00 6.00 6.00 6.00 6.00 6	3929933040 2014017014022027028030C32C 5014024025036C34059061062C 1016C20021026031C34035037 1043142 3144155	50 590515433 390415420540	55101121154			
11.5	2.0 5.38-08 2.7 7.29-06 2.1 2.20-07 2.0 11.5 1.10-0.07 2.0 11.20-0.07 2.1 1.20-0.07 2.1 1.20-0.07 2.1 1.20-0.07 2.20	3029033040 2014017018022027028030030 501402402503603805-0616620 1016020021026031034035037 4081087102119 7083142	50 50515133 390410420540	\$\$101121154			
2.2 2.2 4.8 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0 4.0	20.0 c. 246-62 11.5 c. 1.02-1.02 12.6 c. 1.02-1.02 13.6 c. 1.02-1.02 13.6 c. 1.02-1.02 13.6 c. 1.02-1.02 13.6 c. 1.03-1.02 13.6 c. 1.03-1.03 13.6 c. 1.03 13.6 3029033040 2014017014022027028030332 50140240250360360540616626 5014020021026031634035037 4081487102119	50 50275133 390410420540	55101121154				
2.7 7.438-03 2.6 8 8 8 8.508-03 2.0 1.256-03 4.1 1.156-03 4.1 1.2 1.566-03 4.1 1.366-03 4.1 1.	2.4 7.4 20.0 2.4 1.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4 2.4 2	2014017014002027028030032 2014024025036038034035031 1016020021024031034035037 7043142 3144155	50 5075133 350410420540	55101121154			
11.5	11.5	2014017016022027028030232 501402402603603603604061662 1016020021024031034035037 4081047102119 7083142	50 5075133 390410420540	55101121154			
2.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	11.5 (10.20 + 0.	501+02402503+009+0610620 101402002102+03103+035037 40810+7102119 70831+2	390416420546	55101121154			
11.5 221-27 25.6 2	11.5 1.021-17 2.0 1.011-17 2.0 1.011-17 2.0 1.011-17 3.1 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.001-17 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0	10196200210260310340350370 4081687102119 7083142 8148155	390410420540	55101121154			
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2.0 1.255-0.7 1.556-0.7 1.	2.0 12.55-07 1.4 1.398-0.07 1.2 1.368-0.7 3.1 1.368-0.7 5.0 1.0 1.358-0.7 5.0 1.0 1.358-0.7 5.0 2.248-0.7 6.0 2.248-0.7 6.0 2.248-0.7 6.0 2.248-0.7 6.0 2.248-0.7	314155				:	
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1.5	1.4 1.385-07 1.4 1.385-07 1.4 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5 1.5	6717					
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1.5 E E E E E E E E E E E E E E E E E E E	1.566-07 4.1 1.966-07 4.1 1.966-07 1.0 1 1.966-07 1.0 1 2.00-07 2.10-07 2.246-07 0.0 2.246-07 0.0 2.246-07 0.0 2.346-07	0132					
17.2 1.958-0.7 2.1	17.2 1.655-0.7 9.1 1.756-0.7 9.1 1.756-0.7 9.2 2.026-0.7 2.7 2.026-0.7 0.0 2.246-0.7 0.0 2.246-0.7 0.0 2.246-0.7	3 250 351 351 501 501 5157					
1.75E-07 1.5E-07 1.5E-07 2.1E-07 2.7 2.25E-07 2.0 2.24E-07 0.0 2.24E-07 0.0 2.24E-07 0.0 2.24E-07 0.0 2.24E-07 0.0 2.24E-07 0.0 2.24E-07 0.0 3.01E-07 0.0 3.01E-07 0.0 3.01E-07 0.0 3.01E-07	10.8 1.35E-37 10.8 1.34E-37 10.8 2.28E-37 10.8 2.26E-37 10.0 2.29E-37 10.0 2.29E-37 10.0 2.29E-37 10.0 2.39E-07 10.0 2.39E-07	37.1.7744034034035045036046	061071151251	341411521531	60		
1.347-67 1.38-1.056-137 1.38-2.116-137 2.37-2.298-137 0.0 2.248-137 0.0 2.548-107 0.0 2.548-107 0.0 2.48-107 0.0 2.48-107 0.0 2.48-107 0.0 2.48-107 0.0 3.218-107 0.0 3.218-107 0.0 3.218-107 0.0 3.218-107 0.0 3.218-107 0.0 3.218-107 0.0 3.218-107	10.56 - 0.7	1795 63710730 460 86696 6921081	11139147	1			
2.00	10.8 1.556-37 4.4 - 2.028-97 4.5 2.028-97 6.0 2.246-37 6.0 2.246-37 6.0 2.246-37 6.0 2.566-97 6.0 2.0 2.566-97 6.0 2.566-9	-54 CAACATCA 9078082114118					
2.25 - 9.3 2.7 - 2.25 - 9.3 2.7 - 2.25 - 9.3 0.0 - 2.25 - 9.3	5.4 - 2.02E-97 2.7 2.2E-07 0.0 2.29E-07 0.7 2.34F-07 0.0 2.47E-07	60510=3056066268074085C911	041131231271	37146150			
2.116-03 2.246-03 2.346-03 2.346-03 2.366-03 2.366-03 2.366-03 3.316-03 3.316-03 3.316-03	2.20E-07 2.29E-07 2.29E-07 2.39F-07 2.47E-07	25 70 72 75 0 76 0 76 0 51 0 51 0 51 29 1	21135144151-				
2.20E-0.7 2.346-0.7 2.346-0.7 2.356-0.07 2.346-0.7 2.346-0.7 2.346-0.7 3.316-0.7 3.316-0.7 3.216-0.7	2.246-07 2.346-07 2.446-07 2.476-07	3144101031161221241261451	90				
2.244-07 2.444-07 2.564-07 2.446-07 2.446-07 3.016-07 3.016-07	2.345-07 2.345-07 2.475-07 2.565-07	3637112117					
2.34-07 2.56-07 2.65-07 2.46-07 2.48-07 3.316-07 3.316-07	2.476-07 2.476-07 2.506-07						
2.576.97 2.566.03 2.766.03 2.456.03 2.456.03 3.116.03 3.116.03 3.206.03	2.506-07	0					
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Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose = 3.0 x $10^5~\rm rads$; I_E = 1 μA) Figure 82.

2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	013336642075C87 013336642075C87 012022023C34C40049065191119121		K - 2005 01		COVAT. (2)	
2.000000000000000000000000000000000000	13336542075C87 1202203C34540049065101119 13608.05466C062089089133		****	00 305 700	91.59	
20000000000000000000000000000000000000	13336542075C87 1202203C34540049065101119 1350310546C662089089133					
00000000000000000000000000000000000000	13336642075C87 12022023C34C40049065101119 350910546C66C6520879831					
6.00 6.55%-01 6.00 6.55%-01 6.00 6.00 6.00 6.00 6.00 6.00 6.00 6.	13336642075C87 12022023C35460049065101119 135081054C6C052087089133					
20000000000000000000000000000000000000	13336942075C87 1202203C345400049065191119 135081054060065191119					
20000000000000000000000000000000000000	13336642075C87 12022023623604065121119 350410546C66262089933					
2.6	13336642075687 1202202363464065101119 350410546C662603939133					
2000 000 000 000 000 000 000 000 000 00	13336642075C87 12022023C34C40049065101119 13508.05.4C6CC62089089133					
0.00 6.00 6.00 6.00 6.00 6.00 6.00 6.00	13336642075687 12022023634640049065101119 13508105466662087089133 —				1	
2000 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	13336942075C87 12022023634540049065101119 3504105566C062082099133 —					
2.6 0 1 2.4 6 0	13036042075C87 12022023034040049065101119 3504105406C062082089133					•
2.4	13336642075C87 12022023C34C40049065101119 35041055C6CC62082089133					
2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2	12022023C35640049065101119					
2.4 1 1.2 2.0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0	35041054C&CC62082089133	21				
6 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4						
2.4.4.6.6.01 2.4.6.6.01 2.4.6.01 2.4.6.01 2.4.6.01 2.4.6.01 2.4.6.01 2.4.6.01 2.4.6.01 2.4.6.	.011015216027029631033054C59162143	62143				
6.1 2.4 6.01 6.01 6.01 6.01 6.01 6.01 6.01 6.01	.01601732333334951086125132154	54				
5.6 8 1.45 9.1 1.45 9	.014032037091140142152	-	-		!	•
2.4.4.5.8.9.1.4.5.9.1.4.5.8.9.1.4.5.9.1.5.9.1.4.5.9.1.5.9.1.4.5.9.1.5.	024025014077090126136141157160	0.9				
2.4	.021324382684694399119149					
2.5.4 2.2.5 8 9.1	100134135138149155					
2.5 2.2 E 2.	.014)74091695136127130153					
2.3 % C. 1	04406+06706507607369668107134123139147150	141231391471	.50			
4.1 2.96 01 4.1 2.96 01 4.1 2.90 01 0.7 2.92 01 0.7 2.92 01 1.4 3.92 01 1.4 3.93 01 1.5 3.93 01 1.6 3.93 01 1.7 3.93 01	-023044053057071C45C92115120153	¥ 1		:		
6.1 2.966 01 6.11 2.966 01 6.11 2.906 01 1.4 3.066 01 1.4 3.066 01 1.4 3.066 01	. 3+304+64757207413+113115127137	11				
0.7 3.06 01 0.7 3.06 01 1.4 3.25 01 0.7 3.06 01 0.7 3.06 01	.05567-645117122131146					
2.405 01. 0.7 3.00+ 01. 1.4 3.285 01. 1.4 3.285 01. 0.7 3.515 01.	.0~5051 01705 405 6078 105 145 156	-				
0.7 2.925 01 0.7 3.964 01 1.4 3.285 01 1.4 3.285 01 0.0 3.515 01	354363134113124126					
10.4	OSS					
1.4 3.185 01 1.4 3.285 01 0.0 3.515 01	***	1	1			
2.4 3.28E ol.	.093110					
0.0 3.51E UI	344111					
0.0 3.515	103		1			
0.0 0.0 0.0						
100	Pri Ci					
4.115 01	183					
4.23E 01						

Histogram of $\rm I_B/I_B^2$ Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose = 3.0 x $^{10^5}$ rads; $\rm I_E$ = 1 10 A) Figure 83.

0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0		Let	906306707EC79 9073C76115 1114 1109117124126 1119117124126 1119127146	#EDIAN 3.004E-01 067100 103	#EAN 2.5676-01	5.507t-02	COVAR. (2)	
000000000000000000000000000000000000000		68 45066 105205305605 1305205305605 1305205305605 1305205305605 1305205305605 1305205305605 130520530505 130520530505	906306707EC79 9073070720899E 9073076115 1114 5120117124126 119127146	100				
000000000000000000000000000000000000000		68 45066 45066 45066 45065 2304304604307 4407 4407 4407 4407 4407 4407 4407	3063067078079 3971072089989 307307307197 1114 1109117124126 312212911148	100		1		
000000000000000000000000000000000000000		68 65066 6105205305605 7400470565305605 7400470565305605 74004070560910 740040560910 740040560910	9063067078C79 907307072089999 9073076115 1114 51209117124126 11912146	100				
00000000000000000000000000000000000000		68 45066 45066 2305205305605 2305305005 2305305005 2305305005 2305305005 2305305 23055 2305305 23055 23055 23055 23055 23055 23055 23055 23055 23055 23055 23055 23055 23055 23055 23055 23055	9063067078C79 03710720899E1 1073C76115 1119 1119111724126 5122129131146	100				
00000000000000000000000000000000000000		66 4506 4506 4506 4506 4506 4506 4506 45	3063067078079 3971072089989 3073076115 1114 51212911148	100				
		68 6506 6404 6404 6404 6404 6404 6407 6407 64	9063067078C79 3371072089 GE4 3073C76115 5109117124126 5127146	100				
00000000000000000000000000000000000000		45066 45066 45066 45066 2304306604937 4404140505309 3304334 640740711011 640740711011	9063067078079 037107208999 1114 111911174126 5122129111149	100				
000000000000000000000000000000000000000	-1 :	68 45066 5105205305605 1304504604937 14404 765665 704 14404 765665 704 14404 76966 704 14404 76969 704 14704609 704 704 704 704 704 704 704 704 704 704	9063067078079 907307072089989 9073078115 1114 5129117124126 5127146	100				
0000		68 45066 59040 5904304604937 5904304604937 5904304041930 64074042510310 64074041031041041041041041041041041041041041041041	9063067078C79 0371072089 989 073C76115 1119 1119 122129131146	100				
000		68 45066 510520305605 130430460530 130430460530 13049101110110 6407405509110 194060510410	3063067078079 371072089989 3073076115 1114 5120121174 11191214	100				
		68 45066 15105205305605 15404705605 14404705605 14404705605 1440470505 14404705 1440	906367078C79 3371072089GE 1114 1119 1119 1119 1119 1119 1119 111	100				;
		68 45066 1505205305605 1505205305605 144047050505 14404705051011 1940405410711011 04074092011011	9063067078079 07307107208999 1116 1119 1119 1119 1124 1119 119121	100				
		45066 5105265305605 5105265304 4204705C65311011 64074092C941 7734609110491	3063067078079 3371072089999 9073078115 1114 1114 11169117124126 5122129131145	100 15¢	•			
1		500505305605 300506605307 4404705005705 3306310711011 64074092051	9063067078079 907307808998 1114 1109117124126 1122129131145	103	•			
**************************************		7107202302903 2304304604337 2304304004337 3706412711011 6437409266043 7739609110412	305300 (0/80/4 3071072089 98(1114 1109117124126 5127129131145	103			ī	
24-4-04-20-04-4-4-4-4-4-4-4-4-4-4-4-4-4-		2304304664937 4404765665708 4306410711011 640740426910	3371072089 GEG 9072076115 1114 5109117124126 5122129131145	103				
414144 # # # # # # # # # # # # # # # # #		4404705005705 970410711011 640740920910 9240940650911	9073C76115 1114 9109117124126 5122129131145 9137146	144156	•	;	1	
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4-1-4-2-2-4-4-4-4-4-4-4-4-4-4-4-4-4-4-4-		64074092(3010) 94694655(991) 7709609110912	5125129131145 5122129131145 5137146	144156	•	1		
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		170000000000000000000000000000000000000	2010 2011	13001212000				
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		-02335556 31411-2157	15.7					
		.91201532223335341Ge2121125132140	5 34 1Ge 21 21129	132140				
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	12.							
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Histogram of $h_{\rm FE}/h_{\rm FEO}$ Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose = 3.0 x 10^5 rads; $I_{\rm E}$ = 1 mA) Figure 84.

ON.	PE. R.	125.1		MEDIAN 9.7875-03	MEAN 9.2716-03	STD. DEV. 2.3985-03	COVAP.(%) 25.87	
C	0	1.54-04						
•	0.0	-40-365-04-						
0	0.0	1.115-03	•					
	0	1.546.33	•					
0	0	2.6703						
, -	0.0	2 - 4 33						
, c	0.0	3-175-03						
٠.	Ç	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1						
		2 - 1 - 1 - 2 - 2 - 2 - 2 - 2 - 2 - 2 -	•					
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) 1		CO 100 4	•				1	decouped to the contract
			0.0000000000000000000000000000000000000					
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	1	20-375-0	0.11014016618068650642	CA34.03.05.04.03	ACLASE GALGES			
; (*)	- 6.4	- G - 3 2 E - 0 3 - 1	-,012015024625026031054034655036057074080031077031087101102	204609-00-00-00-00-00-00-00-00-00-00-00-00-0	Deliberturen	201101		
~	ai	D. 345 - 03	.0190200201510390400000000000000001131030	5016116905907				
.4	;	7.314-03	.049121122140154155					
J	5-7	7.745-03	.6771 30135142					
-1	J . t	8.275-33	.143149					
r ~		8-14-5-33	.125132134139140157160					
4			044111141152153					
. #	7.7	5.135-33	.0.1113138147					
_	1.7	1.325-52	.03-032554692137127150					
4	4.6	1.17-02	. 3-705003705509603909095096166115137144146	6166115137144	146		-	
c	3	1.11-52	044044045049667771373082134104114120122123129131135145151	4109114120122	123129141135	145151		
~	8.1	1.15-32	.034369C79CPC2641C0139116118124126156	8124126156				
	- 4.7	- 1.212-02	. 9517c4(6e(93103129112					
1.	7.6	1.205-32	.04505205305505066376372374676351097	1601509				
	6.3	1.3-1-32	.363379117					
c	0.0	1.350-02						
_	7.0	1 - 4 35 - 12	.110					
Ċ	0.0	1.455-02	•					
0	0.0	- 3 * * + E - 0 5 -						
0	0.0	1-545-32						
0	0.0	1.53F -: 32	•					
0	0.0	1.546-32					1	:
· つ	0.0	1.695-02						
10	0.0	1.73E-02	•					
÷	0.0 ·- ·	1 . 7 3 E						
^	0.0	1.955-32	•					
-								,
7 7 1								
					C.	20	25	

Histogram of $\Delta(1/h_{FE})=\Delta I_B/I_C$ Illustrating the Variation in the Radiation Sensitivities Among the 2N930 Transistors of Different Wafers (Dose = 3.0 x 10^5 rads; $I_E=1$ mA) Figure 85.

0.0. CANTA 151 IE - 304/GE O V	1.45 1.65		-							
0.0 -2.775-07 0.0 -2.775-07 0.0 -2.775-07 0.0 -2.75-07 0.0 -2.75-07 0.1 -2.05-07 0.2 -2.75-07 0.3 -2.05-07 0.3 -2.05-07 0.4 -2.05-07 0.5 -2.05-07 0.6 -2.05-07 0.7 -2.05-07 0.8 -2.05-07 0.8 -2.05-07 0.9 -2.05-07 0.9 -2.05-07 0.9 -2.05-07 0.9 -2.05-07 0.9 -2.05-07 0.0 -2.05-07	242 242 242 242 242 242 242 242 242 242			3UAVC6= 0	>	MED1#N -1.8136-07	MEAN -1.7836-07	STD. DEV. 2.646E-08	COVAR. 12)	
0.0 - 2.77=0.0 0.0 - 2.77=0.0 0.0 - 2.77=0.0 0.0 - 2.01=0.0 0.0 - 2.01=0.0	2.242.24.22.24.24.22.24.24	,								
0.0	2.299 2.291284 2.291284 2.291284 2.291284 2.291284 2.291285284 2.291285284 2.291285284 2.291285284 2.291285284 2.291285284 2.291285284 2.291285284 2.291285284 2.291285284 2.291285284 2.29128428528892892893838389 2.2912852888892892893838383 2.291281281281 2.291281281281281281281281281281281281281281								1 : :	
0.0 - 2-01=-07	2.19 2.29 2.29 2.29 2.29 2.29 2.20									
9.7 -2.11-37 -2.41-37 -249 9.7 -2.11-37 -2.41-37 -249 9.7 -2.16-37 -2.41-37 -249 9.7 -2.216-37 -249 9.7 -2.216-37 -249 9.7 -2.216-37 -249 9.7 -2.216-37 -249 9.7 -2.256-37 -249 9.7 -2.266-37 -249 9.	2.99 2.7.291284 2.29513 2.29513 2.29513 2.29513 2.29522 2.25522222 2.2522222 2.2522222 2.2522222 2.2522222 2.2522222 2.2522222222			1.						
0.0	234 235 235 235 235 235 235 235 235 235 235	.,		•						
0.0	281284 281284 281284 281284 281303307308314917334 311319 311319 31228527282327337344245253635360 27122827225431031932333343358 2712282725443103223334435238 27122827254431032233343353 27122827254431032233343333 2712282725443103233343333 2712282725443103233343333 27122828222410592263751 2712282324254105972833 271228242542527254 2712282425257243344353 271228242525242525725 2712282642525272534 271228242525272534 271228242525242525733 271228242525242525733 271228242525242525733 2712822 271282 27128	: `								
1.2	291284 2291330736931417334 27 287 27 287 27 287 27 287 27 287286286316316326326 27 2728628282923193392931353586 27 2728628282923193392931353586 27 272862828282319339239231353586 27 272862828282319338239383539582941349397 27 272862828282823193382383838383 27 27286282828282319382828282382382382828282828282828282828	0								
11.	231284 231284 2313133 2313133 2313133 2313133 2313133 2313133 2313133 2313133 2313133 23131333 23131333 231313333 2313133333 2313133333333	-	- 1	1						
5.7 2.51E-57 289 5.7 2.51E-57 287 1.4 -2.205-77 289 5.0 -2.055-77 27.222228610014032036 2.8 -2.055-77 27.222286210014032036 2.9 -2.055-77 27.222286210319334534589 5.0 -1.055-77 27.222286210319334539398 5.1 -1.74-70 2.2224286292031933393939398398 5.1 -1.74-70 2.2224334629293032339393933983983983983983 5.1 -1.74-70 2.222433462628626271273214345 5.0 -1.655-77 2.222433346289393 5.0 -1.655-77 2.2224334628283 5.0 -1.655-77 2.2224334628283 6.0 -1.255-77 2.2622 6.0 -1.255-77 2.2622 6.0 -1.255-77 2.2623 6.0 -1.255-77 2.2622 6.0 -1.255-7	225 225 225 225 225 225 225 225 225 225	. ~								
1.42.25-37	7. 284.13 7. 284.13 7. 284.13 7. 284.13 7. 12.22.22.22.44 7. 27.22.23.22.47 7. 27.22.23.23.23.23.43.25.36.35.36 7. 27.22.22.23.13.23.23.23.23.33.35 7. 27.22.22.23.23.23.23.23.23.23.33.23.33.23.2									
1.42.2.0 or . 289313 5.0 -2.16 or . 21303307308314317334 1.42.2.0 or . 21303307308314317334 1.42.0 or . 21302307308314317334 1.5. 02.0 or . 21302303307308314317334 2.8 -2.0 0r -0.7 -2.0 or . 2120202231347 2.1 -1.4 or . 0.7 -2.0 or . 202020232347 2.1 -1.4 or . 0.7 -2.0 or . 2020202232347 2.1 -1.4 or . 0.7 -2.0 or . 20202022323233330343353 2.1 -1.4 or . 0.7 -2.0 or . 202020202323333343353 2.1 -1.4 or . 0.7 -2.0 or . 2020202022323333343353 2.1 -1.4 or . 0.7 -2.0 or . 2020202020202020202020202020202020202	07 285413 07 210282941031632026 07 27528272241 07 2752822951247 07 27528272247 07 27528272247373743234323438 07 275282728247352737374323435350 07 27528272242737374345 07 2752827224275272374345 07 275282722427272727274345 07 27528272242727272727274345 07 2752827224272727272727274345 07 27528272242727272727274345 07 2752827224272727272727274345 07 27528272242727272727274345 07 275282727272727272727274345 07 275282727272727272727274345 07 275282727272727272727274345 07 275282727272727272727274345 07 2752827272727272727274345 07 27528272727272727272727274347777277277277277277277727			•		1			1	
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0.0 -9-65-30 0.7 -9-145-09 .223 0.0 -6-25-09 . 0.0 -6-115-09 . 0 5 10 15 20	04 .223 04 .223 04 .223 05 .20 10 .15 .20 5(3) Are Outside the Hange of the Histogram			•						
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0.0 -6.02F-04 . 3.0 -8.11E-04 . 0 0 5 10 15 20 20 . 0 15 20 -8.11E-04 . 0 5 10 15 20 . 0 15 20 . 0 15 20 .	03			Ĭ						
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5.0 -E.IIE-04 . 5 5 10 15 20 FILLINGTO DEVICE(3) ARE OUTSIDE THE MANGE OF THE HISTOGRAM	0 5 10 15 20 20 5 10 15 20 5 10 15 10 15 10 15 10 10 10 10 10 10 10 10 10 10 10 10 10	*	Ţ							
5 10 15 20 FULLINITION DEVICETOR ARE OUTSIDE THE VANGE OF THE HISTOGRAM	0 5 10 15 20 20 5 10 15 20 5 13 1 5 5 13 1 5 5 13 1 ARE OUTSIDE THE NANGE OF THE HISTOGRAM	2								
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FULLINITAL DEVICE(1) ARE OUTSIDE THE RANGE OF THE HISTOGRAM	TE FOLLOWING DEVICETOR AND OUTSIDE THE MANGE OF THE HISTOGRAM ODDATA - 1.27 CE-0.0	~		C	v	10	15	20	52	
	009071 - 1.27 CE-00	1 4	Fallow C. Call Mr.	ARE OUTSIDE TH	F SANGE FF	THE HINTSHAM			: -	
	000013 -1.2755-03	-	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	מי מינים מינים מינים	1000	- Augo 1014 Jul				

Histogram of ΔI_B Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6 x 10 rads; I_E = 3 $\mu A)$ Figure 86.

A.C.	PER	TEST		C # # # # # # # # # # # # # # # # # # #	MEDIAN S.317F 00	MEAN 5-647E 30	9. 799E - 01	17.35	
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0	0.0		S						
c	0.0		Co	•					
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N	.)		?	**************************************	4				
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7.		11.0		30530535301337313361					
, n			3.0	.25326123121316316317318320323324332339350357	032332433233	9350357			
r ,	0.0		3 6	52026424644644646464646464646464646464646	333734235335	1		:	
	2.6			21427526327331344246347358	0.0				
	. 1		00	2353255223343423434344355359	65				
. 4	7 - 7		7	_715246253284-21338340351352360	523 ee				
\$,		50	235244751272272355	1				
¢.		4.1.2	5	CC (a) 780769769769769769769769776	(4 ; 5)				
æ	5.7		0	2533275332475757505375					
J	2.6		2	** 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1					
r.	•	2.76	3						
1	-5 -5			. 2.22.34242242200					
J.	2.1		<u>.</u>	- 52/2 'S. 51.245.45.25.00 (6.16.16.16.16.16.16.16.16.16.16.16.16.16					
	, ,		?	4 2 2 2 3 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2		1 1		•	
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כ	0.0	7.75		•					
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7	0	9CC-6	0						
)	0.0	9.215	S	•					
٠.	· · · · · · ·	4.4	S						
,	0.0	9.02t	Ç	•					
645				u O	0	u\ -	67		

Figure 87. Histogram of I_B/I_B Illustrating the Variation in the Radiation Sengitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6 x 10^6 rads; I_E = 3 μA)

	CENT	is in	.E= 3MAVC8= 0.V	ME01AN 5-1126-01	01 5.082E-01	STD. 0EV.	COVAR.(E)	
			!					
O	0.0	3.4 85-01						
9	0.0	3.565-03		!			!	
o 1	0.0	3.655-01	•					
٠,	9	30 (35 - 31	•					
5 0	200	3.308-01						
9 13	000	3.5.5-01	•					
4	0.0	-10-17-0-1	•					
, 0		10- 121						
_	0.7	4 - 435 - 01	.276					
0	0.0	4.375-01	!					
en.	2.1	10-20-7	. 233228262					
0	7.1	10-214.5	.227223230234241242254264266267	242254264266267				
0	• • •	4.5701	. 224231232234243245251255271	245251255271		***		
٠	4.3	4.556-01	.219236252257276278	27.9				
3	7.1	4.74E-01	.225229240253258260269273779290	260269273779280				
•	2.6	6 - E2F = 31	. 22523578 37245247.	. 225235237245247244250259263265272276277	77247			
+ 1	5.0	TC11.	-217245263355					
2	4.5	10	.2222612751335					
		5.165-01		364351332380				
. ~		5.246-31	356666666666666	ことのこのこうとうしょうようしょうしょうしょ コンプラン・ファンション・ファンション・ファンション・ファンション・ファンション・ファン・ファン・ファン・ファン・ファン・ファン・ファン・ファン・ファン・ファ	**			
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6	4.0	5-416-31	.28129333136 1310317318524354	317318524354				
w.	. s.	5.505-01	.245296291312341					
-	-6.6	- \$0-365.5	247296307314328336345	336345				
.	ر د د	5.565-01	.24224F3023C6313316319	316319				
	5.3	5.775-22	. 2 3 2 2 5 4 3 3 3 3 6 3					
		10-186-6	. 304	9: 4: 1 2: 2	-			:
٠,		5-946-02	. 305					
٠,	0 6	10-306-01						
	0	6-175-01						
		10-16-01						
9	0	6.34E-01	1				***************************************	
0	0.0	6-426-01	Ι.					
•	0.0	6.514-31	•					
1	0.6-	- 5.59c-31						
0	6.3	0.57E-31	•					
145			5 6	10	15	20	25	

Histogram of h_{FE}/h_{FEO} Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6 x 10⁶ rads; I_E = 3 mA) Figure 88.

0.00 4.10=63 0.00 4.10=63 0.00 4.10=63 0.00 4.10=63 0.00 4.10=63 0.00 5.17=03 0.00 5.17=03 0.00 5.17=03 0.00 5.17=03 0.00 5.17=03 0.00 5.17=03 0.00 5.17=03 0.00 6.13=03 0.00 6.10=03 0.00 6.00=03 0.00 STD. 0EV. 8.452E-04	11.39	
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.0		
0.0	1	
20.00		
200 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0		
10.00 10.00		
2. 1		
2		
2.8		1
2.1 6.2 6.2 6.3 6.4 6.4 6.4 6.4 6.4 6.4 6.4 6.4 6.4 6.4		
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2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2		
7.95 FE		
7.4		
7.9 7.420.03 7.0 7.420.03 7.0 8.74.03 2.6 8.74.03 2.1 6.74.03 2.1 6.74.03 2.1 9.04.03 2.2 9.04.03 2.3 9.16.03 2.4 9.04.03 2.6 9.04.03 2.6 9.04.03 2.7 9.04.03 2.7 9.04.03 2.8 9.04.03 2.9 9.04.03 2.0 9.05.03 2.0 0 1.01.03 2.0 0 1.01.03 2.0 0 1.01.03		
2.6		
2.60 2.60 2.61 2.61 2.61 2.61 2.61 2.61 2.61 2.61		
2.8 8 4.27 1.3 2.2 1.4 6.0 2.2		
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2.1 8.55-03 .31343. 2.1 8.55-03 .31343. 2.8 9.105-03 .291307329. 2.0 9.45-03 .29128730835. 1.4 5.50-03 .234259. 0.0 9.35-03 .234259. 0.0 9.35-03 .234259. 0.0 1.016-03 .00 .00 .00 .00 .00 .00 .00 .00 .00 .		
2.1 8.54-0, 241307324 6.7 9.06-03 .235 7.8 9.16-03 .235 1.4 9.56-03 .254259 0.0 9.56-03 .254259 0.0 9.56-03 .254259 0.0 9.56-03 .254259 0.0 1.016-02		
6.7 9.048-02 .245 7.8 9.19(-5) .29128730836-09-09-09-09-09-09-09-09-09-09-09-09-09-		
2.8 9.195-03 .2912k73C8354 1.4 9.26=03 .254259 1.9 9.956=03 .254259 0.0 9.956=03 .254269 0.0 1.056=03 .254269 0.0 1.056=03 .254269 0.0 1.056=03 .254269		
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Too, DOLLINGTON CONTROLLED AND PUBLISHED BRANCE OF THE RESIDENCE OF CONTROLLINGUAM

Histogram of $\Delta(1/h_{FE}) = \Delta I_B/I_C$ Illustrating the Variation in the Radiation Sensitivities Among the 2N2905A Transistors of Different Wafers (Dose = 5.6 x 10^6 rads; $I_E = 3$ mA) Figure 89.

THE RESERVE OF THE PROPERTY OF

	: :		ĺ											1	30.
10 APA 73															
	COVAR. (E) 0.20														25
35	STD. 0EV. 2.787F 01														02
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F4000	NEDIAN 1.387E 02							336.141 237248261268332337339340344345.44355 20521722925626924325327330333342350352353356358359	2C72?424074524725727828032132232833134349351360 2092, 5230231235236250253255260273274279323335338 257275355	65270277	64271276				01
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Histogram of Initial Gain, har, Marked to Illustrate the Extent of the har Versus har Correlation [Marked Devices Came From the Lower Tail of the har (Dose) Histogram]. [2N2905A, har (10mA) < 64 at 1.3 x 10⁶ rad] The Pronounced Structure in the Histogram is Due to the Different Wafers Figure 90.

DEV ICE	E 2N930	TEST	3F.1	15.8	TEMP 22.		STRESS 0.0	£4000	BRL 344	344		10 APR 73
NO NO	PERCENT	46.51 HF.E		1	IMAVCR= 0.V) = i	>	ME01AN 2.739E 02	MEAN 2.755E 02	STD. DEV. 4.833E O1	COVAR.(E) 0.18	
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ပ	0.0	1.21E 0	2	•								
0	0.0	1.32F 0	2 9									
0	0	1.425.0	~ :	•								
اد		1.565	2 6									
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ي. اد	3.1	1.93E C	2		6132	11511	43					
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^	•	2.14E C	~				6138150					
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Histogram of Initial Gain, h_{FEO} , Marked to illustrate the Extent of the hFEO Versus hFE Correlation[Marked Devices Came From the Lower Tail of the hFE (Dose) Histogram]. [2N930, h_{FE} (1mA) \le 64 at 3.0 x 10^5 rad] Figure 91.

- 大概

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Histogram of Initial Gain, hreo, Marked to Illustrate the Extent of the hreo Versus hrec Correlation[Marked Devices Came From the Lower Tail of the hre (Dose) Histogram]. [2N709, hre (ImA) < 19 at 1.3 x 10 rad] Figure 92.

18 1 1 1 1 1 1 1 1 1	15 17 18 18 18 18 18 18 18	2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2									
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Histogram of Low Dose ΔI_B , Marked to Illustrate the Limitations of the Low Dose Screening. Marked Devices Came From the Upper Tail of the High Dose ΔI_B Histogram (2N930, High Dose – 3 x 10^5 rads) Figure 93.



	-										
9	CENT	TEST 16	33 1E	IE- 3UAVCB- 0 V	A 0 *83		MEDIAN MEAN -9.400E-09 -9.434E-09	MEAN -9.434E-09	\$10. DEV. 3.557E-09	COVAR.(8) 37.70	
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_	4.6	-1-146-04	•	23 3 2 2 2 3 1	8 - 2 9 7 E						
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•	8.0	-1.07E-03	7	2902 20431	43123	546347348359	53				
1.5	9.6	-1.326-03	3	22322622	92352362	382392953,	23226229235236238239295324335342350351255356	11255356			
	-	-0-304.		122192833283	33283363	6317243318160	09				
17	7.5	-4. 33E-04		22723733	03313323	. 2272313303313323333343453495352351	49352357				
20	6 .5	-6.465-09	•	21721822	222 52 34 20	21721822222553426422233338353	38353				
	2.0.	-7.39E-09	•	2162693							
~	7.	-7.325-09	•	22423224	12432552	562572622	. 224232241243255256257262263266267271				
CI	6.5	-6.75E-09		54524624	72482502	.242246247248250251268278279280	79280				
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Histogram of Low Dose $^{\Lambda I}_{\rm B}$, Marked to Illustrate the Limitations of the Low Dose Screening. Marked Devices Came From the Upper Tail of the High Dose $^{\Lambda I}_{\rm B}$ Histogram (2N2905A, High Dose - 5.6 x $^{10}_{\rm C}$ rad) Figure 94.

1.356.03 1.356.	0 0.0 0.5778-00 0.0 0.0 0.5778-00 0.0 0.0 0.0 0.5778-00 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0	0	CENT	TEST 33	3	WIAVCRs 3 V		MEDIAN	MEAN	\$10. DEV.	COVARGIE	
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Figure 96. Histogram of the Initial Bias Currents Illustrating the Variation Among the Op Amps

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0	0.0	-9°15E-04				The second section is a second section of the second section s	AND THE PERSON NAMED AND ADDRESS OF THE PERSON NAMED IN	- compared to the compared to
	0.0	-8.74E-04	•					
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1	0.0	7.92E-04						
0	0.0	-7.51E-04	•					
~	1.1	-7-116-34	.234293					
'n	1.7	-6.70E-04	236249300					
	2.2	-6.29E-04	.20822927290					
'n	2 · 8	-5-38E-34	.242262274280397					
ا د	3.3	-5.47E-04	-178195252554302309		The second secon			
16	8.5	-5.06E-04	.162168172177188193206228237245247291397296388391	3724524729139	1729638391			
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_	6.1	-4-25E-04	.182185209222243256257264268284393	68284303	•			
07	11.1	-3.84F-04	•1751 A119120321222023024025028326524537737531384385387392344	5028326524537	73753R1384385	187392394		
12	6.7	-3.43E-04	.167176192204216233263294236389395396	36389355346				
12	1.9	-3:02E-34	-1-7418420121921925231235238281281308-	38281281308-				
6	16.6	-5-47E-04	.165169189202211217221224244247248251253261299301304378383	4424724825125	32 61299301304	378383		
8 1	10.0	-2.2 IE-04	. 1631 7021 32162 322 392467 5526 026 72 702 732 772 78282296305 306	6026727027321	12 18282296305	906		
	2.1	-41 -30E -04	. 1561711731871901972262725825527589380	28267263285	2			
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0	0.0	-9.84E-05	•					
١.	0.0	-5.76E-05	.153					
_	1.7	-1.686-05	.154156382					
	2.5	2.406-05	.152157158160					
į L	1:7	\$0-385-02	.151159139	1				
0	0.0	1.06E-04	•					
0	0.0	1-466-04	•					
	0.0	1.876-04						
0	0.0	2-28E-04	•					
0	0.0	2.69E-04	•					
	0.6	-3.10E-04		:				
_	0.0	3.508-04	•					
	9.0	3.91£-04	.269					
	0.0	#.32E-04	•					
9	0.0	4.73E-04	•					

Histogram of ΔI_B ILlustrating the Variation in the Radiation Sensitivities Among the Op Amps (Dose = 5.6 x 10^6 rads) Figure 97.

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Histogram of ${
m I}_{
m B}$ (5.6 x 10⁶ rad) Illustrating the Variation Among the Op Amps Figure 98.

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Table 77 Rank Correlation Coefficients for Total Dose Damage Prediction (Overview)

X vs. Y (a)	² 2N709	2N9 30	2N2905A
(1/f) Noise	0,3	0.2	0.3
In vs. IB (dose) (p)	0.5-0.94	0.35-0.7	0.96-0.97
$I_B^o \text{ vs. } I_B/I_B^o \text{ (h)}$	(0.6-0.4)	-(0.3-0.2)	0.8-0.7
I_B^o vs. $\{I_B(dose)-I_B^o\}$ (b)	0.2-0.65	0.2-0.4	0.5-0.7
$I/I_B^o vs. (1/I_B^o - 1/I_B)^{(b)}$	0.91-0.94	0.97-0.8	0.98-0.96
ΔI_B (low injection) vs. ΔI_B (high injection)	0.96-0.55-0.2 ^(e)	0.98-0.90	0.90-0.80-0.55 ^(e)
h _{FEO} vs. h _{FE} (dose)	0.56-0.80-0.95 ^(e)	0.36-0.49-0.68 ^(e)	0.97-0.97
h _{FEO} vs. h _{FEO} -h _{FE} (dose)	0.91-0.94	0.97-0.83	0.96-0.95
h _{FEO} vs. h _{FE} /h _{FEO}	-(0.6-0.4)	-(0.3-0.2)	-(0.8-0.7)
h _{FEO} vs. 2h _{FE} /h _{FEO}	0.5-0.6	0.3-0.2	0.8-0.7
1/h _{FEO} vs. 1(1/h _{FE})	0.2-0.7	-(0.4-0.2)	-(0.75-0.6)
I _B (c)	-0.5	-(0.6-0.55)	0.7-0.85
$1_{\mathbf{B}}^{\mathbf{o}}(\mathbf{T})^{(\mathbf{d},\mathbf{c})}$	-0.4	-0.4	0.7-0.8
ΔI _B (due to :T) (c)	-0.4	-0.4-0	0.75-0.8
ΔI _B (due to burn-in)(c)	ù	-0.3 to 0.3	-(0.3-0.2)
Ino (or Byo)	-0.4	-0.3	0.6-0.75
I _{EBO} (T) (or BV _{EBO})	-0,4	-0.3	0.6-0.75
ΔI _{EBO} (due to 11) (or LBV _{EBO})	-0.4	0.2	0.6-0.7
ΔI _{EBO} (due to burn-in)	0		
2N930 ((I/f) Noise		0.3	
Pre- to B I (T)		-0.4	
In (In (T)		-0.4	+

⁽a)Unless otherwise noted, the Y parameter is Radiation Sensitivity $\boldsymbol{\Xi}$ the

change or the relative change in the low injection $I_{\rm B}$. (b) All $I_{\rm B}$ values were taken at relatively high injection . el.

⁽c)AII IB values were taken at low injection level.
(d)"T" indicates other than room temperature.

⁽e) These multiple entries represent variation with emitter current. Arrows correspond to the direction of increasing current.

Table 78 Summary of Data to Illustrate the Radiation Sensitivity of 2N709

r										1			 		
	s cov %	73	37	36		92	52	27		43	21	8.7	41	37	19
	5.6 x 10 ⁶ rads	2.5×10^{-7}	1.1 × 10 ⁻⁶	3.5×10^{-5}		27.1	8.0	2.66		0.20	0.36	0.55	1.1×10^{-1}	3.7×10^{-2}	1.8 × 10 ⁻²
;	rads COV %	79	29	48		62	56	20		48	19	5.9	99	87	21
	1.3 × 10 ⁶	6.5 × 10 ⁻⁸	2.5 × 10 ⁻⁷	1.7×10^{-5}		8.7	5.0	1.8		0.41	0.55	0.70	4.7 × 10 ⁻²	1.8 × 10 ⁻²	1.c x 10 ⁻²
	rads COV %	166	98	43		39	25	7.5		16	8.6	2.7	56	77	36
	3.0 × 10 ⁵ r	3.4×10^{-9}	8.1×10^{-8}	5.0 × 10 ⁻⁶		1.45	1.6	1.24		72.0	0.81	0.35	9.3×10^{-3}	5.3 x 10 ⁻³	3.8×10^{-3}
	1.0 x 10 ⁵ rads			-			•	1			1			-	
		E 0.45V	= 3 µA	= 1 mA		υ = 0.45v	= 3 µA	= 1 mA		= 100 µA	= 1 mA	= 10 mA	- 100 µA	- 1 mA	= 10 mA
		VBE	I E	I H H	Ч	VBE	at H	I I H	L	I.E	38 H	.μ Έ	 H	E ST	H H
			ΔI _B	(Amps.)		_	I B	I a	q		Here and			A(1/hFE) 8	٦

Y

Table 79 Summary of Data to Illustrate the Radiation Sensitivity of 2N930

								,		•	
				1.0 x 10 ⁵ re	rads	3.0×10^{3} ra	rads	1.3 x 10° ra	raus	5.6 x 10° rads	
					COV %		COV %		cov %		COV %
	Ť	VBE =	= 0.45V	7.9 x 10 ⁻⁸	77	2.3 × 10 ⁻⁷	07	3.3 x 10 ⁻⁷	19	4.3 × 10 ⁻⁷	13
∆I _B	36	I E	= 1 pA	4.4 × 10 ⁻⁸	9/	1.4×10^{-7}	41	2.0×10^{-7}	20	2.5×10^{-7}	15
(Amps)	а ¹	ł	= 100 uA	8.7 × 10 ⁻⁷	63	2.1 × 10 ⁻⁶	37	3.c × 10 ⁻⁶	19	3.7 × 10 ⁻⁶	15
		I E	= 10 mA	2.5 × 10 ⁻⁵	53	4.5 × 10 ⁻⁵	41	6.8 x 10 ⁻⁵	36	9.2×10^{-5}	20
		V _{BE} =	= 0.45V	5.7	65	15.0	77	20.0	37	25.7	35
IB] F	I E	1 µA	6.5	r,	18,3	41	23.9	35	32.2	21
O E	~	I _E =	= 100 µA	3.0	45	5.8	31	7.7	18	9.6	15
•		I _E =	= 10 mA	1.6	22	2.1	21	2.7	12	3.2	10
		I _E =	= 100 µA	0.36	34	0.17	24	0.13	18	0.105	16
	3£	I E	- 1 mA	0.50	29	0.30	19	0.23	15	0.19	13
02.ju	Es _q	T. EH.	= 10 mA	0.65	22	0.47	91	0.37	12	0.31	10
		IE =	= 50 mA	08.0	12	0.65	12	0.53	11	0.45	8.4
	1	T _E	= 100 µA	8.9×10^{-3}	63	2.2×10^{-2}	36	3.1×10^{-2}	20	3.9×10^{-2}	16
1/n = 1		T 표	= 1 mA	4.3 x 10 ⁻³	56	8.7×10^{-3}	36	1.3×10^{-2}	20	1.6 × 10 ⁻²	16
	u	l I	= 10mA	2.6×10^{-3}	53	4.6 × 10 ⁻³	40	6.9 × 10 ⁻³	36	9.4×10^{-3}	20

Table 80 Summary of Data to Illustrate the Radiation Sensitivity of 2N2905A

ls COV 7	13	15	10	27	17	5.7	6.7	2.2	2.3	11	11	8.4
5.6 x 10 ⁶ rads	-2.3×10^{-7}	-1.8×10^{-7}	-2.0 × 10 ⁻⁴	4.3	5.6	1.9	0.51	0.53	0.67	7.4×10^{-3}	6.7×10^{-3}	1.0 × 10 ⁻²
ads	21	19	13	17	13	4.9	5.5	5.1	1.9	15	13	13
1.3 × 10 ⁶ r	-6.3 × 10 ⁻⁸	-5.3 × 10 ⁻⁸	-1.2 × 10 ⁻⁴	1.9	2.4	1.6	0.71	0.64	0.80	3.2 × 10 ⁻³	4.2×10^{-3}	5.5 × 10 ⁻³
ads COV %	120	36	19	11	5.4	4.4	2.4	4.5	1.5	31	19	36
3.0 x 10 ⁵ rads	-5.1×10^{-9}	-1.5 x 10 ⁻⁸	-9.1 × 10 ⁻⁵	1.1	1.4	1.4	0.87	0.71	16.0	1.2×10^{-3}	3.1×10^{-3}	2.0×10^{-3}
ads cov 7	250	40	18	7.7	3.9	2.3		i	i	41	18	43
1.0 × 10 ⁵ rads	1.8 x 10 ⁻⁹	-5.7 × 10 ⁻⁹	-5.6 × 10 ⁻⁵	86.0	1.15	1.25	‡.		l	3.8 × 10 ⁻⁴	1.9×10^{-3}	5.7 × 10 ⁻⁴
	$v_{BE} = 0.45v$	I _E = 3 μA	1 E = 30 mA	V _{BE} = 0.45V	E = 3 µA	I _E = 30 mA	I _E = 3 mA	E = 30 mA	I _E = 300 mA	I _E = 3 mA	E = 30 mA	I _E = 300 mA
	2	at H	8 ^I	3	s gI	H	Н	Est	I ∺ [∄] ų	1	6 3F	ч
		∆ IB	(Amps.)	ŀ) E			OZ.		∆(1/h _{FE}) ^ख	

Table 81

Results of Rank Correlations Between Radiation Sensitivity (Low Dose) and Radiation Sensitivity (High Dose)

	Bias	Radiation S I _B (irradia	Sensitivity: sted)- IB	
Device Type	Condition for I _B	Low Dose rad(Si)	High Dose rad(Si)	Correlation Coefficient
2N709	$V_{BE} = 0.45V$	1.7 x 10 ⁵	1.3 x 10 ⁶	0.678
1	$I_E = 3 \mu A$	1.7×10^{5}	1.3 x 10 ⁶	0.663
	$V_{VE} = 0.45V$	3.0×10^5	1.3×10^{6}	0.893
	I _E = 3 μA	3.0 x 10 ⁵	1.3 x 10 ⁶	0.821
2N930	$V_{pq} = 0.45V$	3.0 x 10 ⁴	3.0 x 10 ⁵	0.699
	$I_{y} = 1 \text{ uA}$	3.0×10^4	3.0 x 10 ⁵	0.639
	$V_{BE} = 0.45V$	1.0×10^{5}	3.0 x 10 ⁵	0.752
	$I_{E} = 1 \mu A$	1.0×10^{5}	3.0 x 10 ⁵	0.726
2N2905A	V _{BE} = 0.45V	1.7 x 10 ⁵	5.6 x 10 ⁶	0.329
	$I_{\rm E} = 3 \mu A$	1.7×10^5	5.6 x 10 ⁶	0.675
	$V_{BE} = 0.45V$	3.0×10^5	5.6 x 10 ⁶	0.296
	$I_{E} = 3 \mu A$	3.0 x 10 ⁵	5.6 x 10 ⁶	0.681

Table 82

Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening (2N930)

	3×10^5	5 rads	1 x 1	10 ⁵ rads		
Bias Conditions	Rows R	Devices N	Rows P	Devices M	N(% of Total Sample)	M (% of Total Sample)
	7	2	13	09	1.3	40.3
	7	9	13	09	0.4	40.3
$I_{\mathbf{B}}(\mathbf{V}_{\mathbf{BE}} = 0.45\mathbf{V})$	e	11	14	.63	7.4	42.3
	4	19	15	73	12.8	6.64
	V.	35	15	73	23.5	0.54
	1	1	10	24	0.7	36.2
	2	٧	13	76	3.4	63.1
$^{1}B(^{1}E = 1 \mu A)$	8	17	. 13	76	11.4	63.1
	4	32	13	94	21.5	63.1
	-	-	6	51	1	34.2
$I_B(I_E = 100 \mu A)$	2	٧	10	53	\$	35.6
	3	17	13	81	17	54.4
	7	-	5	39	1	26.2
	7	က	9	87	6	32.2
(1 - 1)	m	9	7	57	9	38.3
TB(TE TO mA)	4	17	7	57	17	38.3
	'n	22	7	57	22	38.3
	9	29	10	64	29	43.0

Table 83

Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening (2N2905A)

		LOW UC	riiaaine as	TON TOSE SCIENTING (SNESOC MOT		
	5 x 1(x 106 rads	1.7 ×	1.7 x 10 ⁵ rads		
Bias Conditions	Rows R	Devices N	Rows P	Devices M	N(% of Total Sample)	M (% of Total Sample)
	2	, †	9	36	2.8	25.5
$I_{R}(I_{F} = 300 \text{ mA})$	ო	15	10	66	10.6	70.2
a a	7	26	10	66	18.4	70.2
	7	8	6	32	5.7	22.7
T (T = 1 mA)	y	16	12	63	11.3	44.7
-B / -Ε	7	23	18	124	16.3	87.9
	3	5	6	25	3.5	17.7
	'n	7	6	25	5.0	17.7
T (T = 3 1,A)	9	16	13	57	11.3	40.4
B'E	7	19	13	57	13.5	40.4
	∞	25	18	105	17.7	74.5
	8	5	12	63	3.5	0.99
$I_{\rm L}(V_{\rm nr}=0.45V)$	4	. 91	16	126	11.3	89.4
b be	'n	22	18	138	15.6	97.9

Table 34

Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening (2N709)

Bias Condition	Rows *R	De- vices N	N(% of Total Sample)	Rows *P	De- vices M	M(% of Total Sample)
I _B at	1	2	1.5	3	3	2.3
I _E = 10 mA	2	4	3.0	6	9	6.8
	5	7	5.3	7	11	8.3
	6	11	8.3	10	33	24.8
	7	15	11.3	10	33	24.8
	8	23	17.3	12	47	35.3
I _B at	1	1	0.75	1	7	5.3
I _E = 100 μA	3	4	3.0	1	7	5.3
	4	7	5.3	3	9	6.8
	7	11	8.3	9	22	16.5
	9	14	10.5	9	22	16.5
	11	20	15.0	12	55	41.3
I _B at	1	1	0.75	1	7	5.3
I _E = 3 μA	2	2	1.5	2	8	6.0
	3	5	3.8	9	17	12.8
	7	10	7.5	9	17	12.8
	9	17	12.8	13	41	30.8
	11	23	17.3	15	84	63.2

^{*}In these histograms, all devices with good data, but such large ΔI_B as to fall outside the histogram plot, were called row 1.

Table 85 Rank Correlation Coefficients for Damage Prediction at 5.6 x 10^6 rads - $\mu\text{A}744$

Change in Bias Current, ΔI_B vs.:	Rank Correlation
I B	-0.061
low frequency noise current	0.091
I_{B}^{o} (22°C) - I_{B}^{o} (-50°C)	0.112
I_{B}° (75°C) - I_{B}° (22°C)	0.157
I_{B}° (75°C) - I_{B}° (-50°C)	0.190
I _B ° (-50°C)	-0.099
I _B (75°C)	0.082
Relative Change in Bias Current, $\Delta I_B/I_B^o$ vs.:	=
I o	C.546
low frequency noise current	-0.316
I_{B}^{o} (22°C) - I_{B}^{o} (-50°C)	-0.403
I_{B}^{o} (75°C) - I_{B}^{o} (22°C)	-0.486
I_{B}^{o} (75°C) - I_{B}^{o} (-50°C)	-0.492
I _B (-50°C)	0.463
I _B (75°C)	0.237

Table 86 Summary of Data Illustrating the Procedure and the Results of the Low Dose Screening for the $\mu\text{A}744$ Op Amp

Rows R	Devices N	N(% of Total Sample)	Rows P	Devices M	M(% of Total Sample)
1	2	1.4	13	56	39.7
2	5	3.5	14	74	52.5
3	9	6.4	14	74	52.5
4	14	9.9	15	106	75.2
5	20	14.2	15	106	75.2

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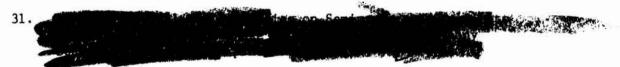
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